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May 1974

HERBICIDE REPORT

Chemistry and Analysis
Environmental Effects
Agricultural and Other Applied Uses

HAZARDOUS MATERIALS ADVISORY COMMITTEE

SCIENCE ADVISORY BOARD
U.S. ENVIRONMENTAL PROTECTION AGENCY
Washington, D.C. 20460

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16. ABSTRACT

Selected herbicides are discussed under the headings of chemistry and analysis, environmental effects, and agricultural and other applied uses.

The groupings employed are based on chemical structure and recognize 13 major groups of herbicides: chlorinated phenoxyalkanoic acids, s-triazines, phenylureas, carbamates, thiocarbamates, amides, chlorinated aliphatic acids, chlorinated benzoic acids, phenols, substituted dinitroanilines, bipyridiniums, arsenicals, uracils, and miscellaneous. Synthesis, analysis, and properties are discussed for each of these groups, and consideration is given to specific analytical methods and to general, multiresidue methods such as gas-liquid chromatography.

Environmental effects of herbicides are described in terms of sources and movements of herbicides; residues in soil, water, and air; bioaccumulation of residues; effects on nontarget plants; and the costs and benefits of herbicide use.

The principal uses of herbicides are on croplands, grazing lands, forests, orchards, aquatic habitats, and industrial sites and other noncrop lands. Each of these topics is covered in detail, and herbicide use is compared with alternative methods with regard to efficacy and economics.

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by the

HAZARDOUS MATERIALS ADVISORY COMMITTEE

United States Environmental Agency

Washington, D.C., 20460

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EPA NOTICE

This report has been written as a part of the activities of the Hazardous Materials Advisory Committee and was initiated prior to the establishment of the Science Advisory Board, of which it is a member committee. The Science Advisory Board is a public advisory group providing extramural scientific information to the Administrator and other officials of the Environmental Protection Agency. The Board is structured to provide a balanced expert assessment of the scientific matters related to problems facing the Agency. Because this is an independent, extramural report, the Agency has no role in its review and approval. Hence, its contents do not represent the views and policies of the Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

PREFACE

The Hazardous Materials Advisory Committee (HMAC) was asked to prepare a comprehensive report on herbicide uses and their environmental effects. The study was to serve as a background for EPA decisions.

The study was first inaugurated in May 1972, and a tentative timetable was developed. Four sections were organized, each consisting of scientists from various disciplines. These consultants prepared drafts that were reviewed by the others and the full Hazardous Materials Advisory Committee.

Only by the cooperation of many persons was the writing of the report made possible. Members of the HMAC who had specific responsibilities were Errett Deck, Leon Golberg and Rosmarie von Rümker. The coordinators of the respective sections were Phillip Kearney, Chemistry and Analysis; David Pimentel, Environmental Effects; and Boysie Day, Agricultural and Other Applied Uses. Leon Golberg, Human Health Effects.

A number of individuals provided advice and assistance in the organization and review of these four sections and in the preparation of the Committee statement. These included William Ennis, Donald McCollister, William Upholt, Gordon Guyer, Rosmarie von Rümker, and Errett Deck.

The roster lists the names of those consultants to whom the Committee expresses great appreciation.

Credit is due to the HMAC staff and to Winfred F. Malone for their work on the report.

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COMMITTEE STATEMENT

INTRODUCTION

This herbicide study was prepared by the Hazardous Materials Advisory Committee in response to a request from the Administrator of the Environmental Protection Agency. Leading scientists in the herbicide field contributed to sections on chemistry and analysis, environmental effects, and agricultural and other applied uses. The purpose of the study is to assess the usage patterns and benefits of using herbicides and to gain greater knowledge of the environmental effects of these compounds. The discussion covers herbicide use, available alternatives, and approaches to understanding and solving problems.

A number of herbicides were considered in the analysis, selected partly on the basis of usage. They included, among others, butylate, Propazine, trifluralin, chloramben, 2,4-D, nitralin, alachlor, linuron, endothall, diuron, atrazine, and propachlor.

The problems of environmental pollution, including chemical pollution, are the result mainly of industrialization, urbanization, and intensive agricultural practices. Pesticides of all kinds constitute about 2 percent by weight of the total chemicals used in our society. Herbicides make up about 50 percent of the quantities of pesticides used in the United States. The major concern in the past was related to the acute toxicity of these various environmental contaminants. More recently concern about possible chronic effects on wildlife, water quality, and other aspects of the environment has intensified.

The purpose of this report is to assemble available information in these several subject areas, to describe and evaluate different approaches to solving problems, and to improve our understanding of the subject. It is hoped that this will assist EPA in evaluating risks and benefits when determining if there is need for regulatory action on a herbicide. This report is a compilation of the thoughts of many individuals. Thus its strength or weakness depends on the individual views of its contributors.

Scope

Herbicides are used to control weeds in croplands; to improve the production of desirable forage in pastures and grazing lands; to control aquatic weeds where they interfere with water use (irrigation, navigation, recreation, etc.); in forestry, to promote the growth of timber by controlling unwanted species; industrially, to maintain utility and highway rights-of-way and to eliminate hazards around oil tanks and railroad tracks; recreationally, to maintain desirable turf on lawns, on golf courses, and in parks; and to control poisonous and allergenic plants, such as poison ivy and ragweed, in the interest of the health and well-being of man.

Herbicides are important tools for suppressing unwanted species of plants. They are used along with cultural practices to provide integrated systems of vegetation management. Although alternatives to herbicides—such as hoeing, cultivating, and crop rotation—have been used for generations, herbicides are valuable adjuncts to these traditional and often laborious methods of controlling weeds. Herbicide use does not substitute for good management practices in farm and ranch operations or in other habitats where weeds need controlling. Herbicide use involves both benefits and risks, which need to be evaluated.

Extent of Use

Current estimates suggest that about 134 herbicides are registered in the United States. Products formulated from these chemicals number in the thousands. In 1970 approximately 391 million pounds of organic herbicides were synthesized domestically. As a specific example, the USDA *Pesticide Review, 1971*, published in March 1972, lists domestic production of 2,4-D in 1970 at 43.5 million pounds. There are 21 herbicides registered for corn, the top two being atrazine and 2,4-D. Data from a survey conducted by the U.S. Department of Agriculture indicate that 76 *percent* of the 64.3 million acres of corn harvested in 1968 were treated for weed control. Comparable figures for other crops in 1968 are as follows: soybeans, 40.6 million acres, 22 million treated; cotton, 10.1 and 9 million; wheat, 55.3 and 21.2 million. Most field crop rates of application in accordance with EPA-registered herbicide labeling vary from 0.25 to 4 pounds per acre.

In the United States during 1970 nearly 1 billion pounds of pesticides (about 50 percent herbicides) were used to control about 2000 pest species, or about 1 percent of the total species. In the process, many nontarget species in the environmental life system are directly or indirectly affected by the use of insecticides, fungicides, herbicides, and other pesticides.

CHEMISTRY

Major Classes of Herbicides

Each currently used herbicide can be categorized on the basis of its chemical structure. The number of groups can vary from 10 to 25, depending on the refinement of the categories. A few exceptions would fall into a miscellaneous group. A suggested classification is shown in Table 1.

Use of Classification Scheme

A proposed new herbicide may be identified with a class based on its chemical structure. Potential problems are associated with various classes. Tests based on prior experience can be conducted early in the research phases to identify compounds that may have potential environmental or health-related effects.

An example of how the above classification system can be used in a decision-making process is illustrated. The detection of TCDD, a dioxin (specifically 2,3,7,8-tetrachlorodibenzo-*p*-dioxin), in 2,4,5-T raised the question whether TCDD might be present in other herbicides. The formation of TCDD occurs in the manufacturing process during the production of trichlorophenol. Therefore it would be logical to examine herbicides in groups I and IX (see Table 1) for dioxin contaminants. Since TCDD formation requires high-temperature hydrolysis and a chlorine atom in the 2-position on the ring, certain herbicides from groups I and IX would not be suspect. The phenol in 2,4-D and related dichlorophenoxy herbicides is prepared by chlorination (i.e., no elevated temperatures are involved); hence herbicides manufactured as such could be disregarded in group I. By this process of elimination, certain herbicides remain suspect for dioxin content. Investigators have analyzed approximately 129 samples of 17 different phenol-based pesticides for TCDD content; no dioxins were detected in 76 percent of the samples analyzed.

As environmental and health-effects issues are raised about various herbicides—such as impurities (e.g., dioxins) or metabolites—the chemical classification system becomes a valuable tool for selecting chemically related herbicides for examination and testing.

Compounds Under Consideration

Some of the major herbicides evaluated in this report with reference to their possible environmental effects are listed in Table 2. Of the 15 herbicides listed, there is a close chemical relationship between alachlor and propachlor, linuron and diuron, atrazine and Propazine, and trifluralin

Table 1. MAJOR CHEMICAL CLASSES OF HERBICIDES

Group	Chemical class	Examples
I	Chlorinated phenoxyalkanoic acids	2,4-D, 2,4,5-T, Silvex
II	*s*-Triazines	Atrazine, Propazine, simazine
III	Phenylureas	Fenuron, linuron
IV	Carbamates	Barban
V	Thiocarbamates	Butylate
VI	Amides	Alachlor, propachlor
VII	Chlorinated aliphatic acids	Dalapon
VIII	Chlorinated benzoic acids	Chloramben, dichlobenil
IX	Phenols	Bromoxynil, DNOC
X	Substituted dinitroanilines	Nitralin, trifluralin
XI	Bipyridiniums	Diquat, paraquat
XII	Arsenicals	Cacodylic acid
XIII	Uracil derivatives	Bromacil, terbacil
	Miscellaneous	Acrolein, endothall, picloram

Table 2. HERBICIDES REVIEWED IN DETAIL IN THIS REPORT

Common name	Chemical name
Alachlor[1]	2-Chloro-2′,6′-diethyl-N-(methoxymethyl) acetanilide
Propachlor[1]	2-Chloro-N-isopropylacetanilide
Linuron[1]	3-(3,4-Dichlorophenyl)-1-methoxy-1-methylurea
Diuron[1,2]	3-(3,4-Dichlorophenyl)-1,1-dimethylurea
Atrazine[1]	2-Chloro-4-ethylamino-6-isopropylamino-*s*-triazine
Propazine[1]	2-Chloro-4,6-bis(isopropylamino)-*s*-triazine
Trifluralin[1]	α,α,α-Trifluoro-2,6-dinitro-N,N-dipropyl-*p*-toluidine
Nitralin[1]	4-(Methylsulfonyl)-2,6-dinitro-N,N-dipropylaniline
2,4-D	(2,4-Dichlorophenoxy)acetic acid, its amine salts and esters
Chloramben	3-Amino-2,5-dichlorobenzoic acid
Butylate	S-Ethyl diisobutylthiocarbamate
Miscellaneous:	
Acrolein[2]	2-Propenal
Copper sulfate[2]	
Endothall[2]	7-Oxabicyclo(2,2,1)heptane-2,3-dicarboxylic acid
Xylene[2]	

[1] Compounds chemically related: alachlor and propachlor, linuron and diuron, atrazine and Propazine, and trifluralin and nitralin.

[2] Compounds of interest because of sites of application (aquatic).

and nitralin. Some of the products listed are of interest mainly because of the aquatic sites of application. Their importance is thus principally related to their potential environmental impact.

ENVIRONMENTAL EFFECTS

Herbicides constitute an important management tool whose intended effects in plant control represent a significant environmental impact that is beneficial in the control of weeds but in some cases adversely affects nontarget organisms. The environmental effects on soil, water, and air, together with the impact on life systems, are discussed in this section.

Sources and Movement

The occurrence of herbicide residues in both target and nontarget areas and their effects depend on (1) persistence, (2) amount used, (3) application method, (4) movement, (5) toxicity, and (6) possible bioconcentration. Although pesticides exhibit a wide range in toxicity to animals, herbicides as a class are generally less toxic than insecticides. The accumulation of certain herbicides does occur in plants, and this can be a hazard. The chances of a herbicide becoming a hazard are greater if it is persistent.

Bioaccumulation of Residues

Use of the terms "bioaccumulation" and "bioconcentration" may conjure up the image of the type of residue accumulation that occurs with the insecticide DDT in the fat tissues of animal organisms. The bioconcentration factor (bioaccumulation) is the ratio of the measured residues in animal or plant (or specific tissues thereof) compared to the residues of the pesticide in the ambient air, water, or soil environment of the organism and/or the various species of food organisms consumed, as specified. The highest bioconcentration factors in animals usually occur in water with chlorinated insecticides; for example, DDT and its metabolite DDE may have a bioconcentration factor of 10^6. Such herbicides as picloram, Silvex, 2,4-D, and dichlobenil appear to bioconcentrate as much as tenfold in fish or other aquatic organisms but not at all in other species. Diuron may have a bioconcentration factor of several hundred. These herbicides degrade in both plant and soil systems.

Data on herbicide residues in wild mammals and birds are scarce. However, domestic animal and bird tissues appear to be free of residues that would be significant for human use.

The terms "bioaccumulation" and "bioconcentration" may be applied to plants. The properties of a chemical used to penetrate and kill insects are generally quite different from those needed to penetrate and kill plants. Insecticides that are nonsystemic poisons are often quite soluble in fats (in order to penetrate insects) but fairly insoluble in water; thus stable compounds may be bioaccumulated in animal fats and be consumed by other animals. Many herbicides are water soluble and do not partition as greatly in favor of fat tissues as do organochlorine insecticides. Degradation of most herbicides leads to more polar products. Many herbicides are systemic, that is, they penetrate plants and thus redistribute residues, especially in the growing portions of the plants, such as leaves and roots. Although many herbicides are rapidly metabolized to nontoxic compounds in plant tissues, some herbicide residues persist at detectable levels.

Residues in Soil

A major problem in assaying herbicide soil residues is the accurate measurement of actual amounts of the compound and/or its degradation products in varying time periods after application. Only a few studies include a wide variety of the most commonly used herbicides tested comparatively in the field. A Southern States Regional Cooperative Study showed that no phytotoxic residues of atrazine, diuron, linuron, or trifluralin persist in soil after 1 year when the herbicides are applied at recommended rates. However, no analytical data were included on nonphytotoxic residues that might have been present.

Herbicide residues are likely to persist longer in the colder areas of the United States and Canada. An example is the carryover of phytotoxic levels of atrazine from the year of application to the next year, which has caused damage to susceptible crops such as beans. In Oregon, studies of chemical brush control with several compounds indicated that detectable residues of picloram persisted for more than a year while the others degraded more rapidly. Herbicide persistence is affected by many variables, including concentration, temperature, moisture, pH, soil type, microbial ecology, formulation, and chemical structure.

Residues in Water.—The most common herbicides used to control aquatic weeds are xylene, copper sulfate, 2,4-D, acrolein, endothall, dichlobenil, and diquat. Few materials are registered for this use because of potential access to potable water supplies and potential environmental problems.

The main potential sources of herbicidal residues in water are direct application, drift from aerial application, runoff from treated land, treatment of ditchbank vegetation, and faulty waste disposal techniques by the manufacturer, homeowner, commercial applicator, or farmer.

Limited pesticide residue monitoring studies have been conducted by various U.S. agencies. Very low levels of residues were found in a few samples, but none were biologically significant in the waters monitored. Herbicide (2,4-D) residues in bottom muds of cold lakes or those with a low oxygen content may persist for months. Eleven streams in the western United States were monitored for 2,4-D, 2,4,5-T, and Silvex. No herbicide residues were found.

A number of chemicals that are persistent in soils are less persistent in water due to the action of ultraviolet light. A herbicide like picloram, which is resistant to degradation in soil, is more easily decomposed by sunlight in surface water, with a half-life ranging from 2 to 41 days, depending on water depth, amount of sunlight, and water quality. More studies on various herbicides concerning decomposition by sunlight are needed to help calculation of their half-life in water.

Residues in Air.—Herbicide residues in air come principally from three sources: (1) spray-particle drift at the time of application; (2) dispersal of herbicides on particles due to wind erosion after application; and (3) gaseous dispersion because of volatility at the time of application or from soil, water, plants, or other treated areas. Items 1 and 3 are most important.

Occasionally, during periods of great wind storms, the accompanying dust storms may deposit small but detectable residues of herbicides—presumably carried over great distances (such as from Texas to Ohio) on contaminated or treated soil particles. Even during normal weather, particulate matter suspended in air may absorb volatile herbicides and then be redeposited on bodies of water or on the ground by rain storms some distance from the original source of the application. Particles from air have been shown to contain 2,4,5-T in amounts of up to 0.04 ppm.

Drift of fine aerosol spray particles and 2,4-D vapors from volatile formulations may be responsible for considerable damage to sensitive nontarget plants surrounding target areas. The presence in air samples of various salts and esters of 2,4-D has been studied in the state of Washington. The volatility of 2,4-D formulations varies greatly from the high-volatile esters to the low-volatile esters and the relatively nonvolatile amine salts. Investigations of crop damage have verified that volatility is a major contributor to 2,4-D drift damage.

The volatility of a given herbicide from various treated surfaces varies greatly, depending on the weather, formulation, and adsorptive capacity of the surface from which the herbicide volatilizes. Generally speaking, soil and other surfaces that adsorb herbicides to the greatest extent allow the least volatility. A large percentage of certain herbicides can be lost within a few hours or days by volatility unless incorporated with the soil.

Impact on Life Systems

The desired effect of herbicides is to kill weeds, retard their growth, or selectively alter the plant cover. Associated with herbicide use are other ecological effects—some beneficial and some harmful.

Although herbicides are intended to control unwanted plants, their effects are not limited to plants. Some animal species are quite susceptible to the direct action of these compounds. The mammal and bird species tested were relatively tolerant to herbicides, but fish and invertebrates were relatively susceptible to some compounds, such as trifluralin and dichlone. The hazard of such herbicides is important and must be carefully evaluated. When emulsified in water, trifluralin kills fish at very low concentrations. When applied to soil, it is strongly absorbed by the soil and presents little risk of water contamination.

Herbicides may affect nontarget organisms within a target area, such as the microorganisms that are important in nitrification and in degrading wastes. However, the current use patterns of herbicides as well as laboratory and field data suggest that herbicides do not constitute a serious threat to the microbial equilibrium of the soil.

Herbicides may reduce or eliminate natural resistance in plants, rendering them more susceptible to attack by pests. For example, red clover and oat strains resistant to pest nematodes lost their resistance when exposed to low levels of 2,4-D.

Herbicides may alter the nutritional content of crops—either increasing or decreasing their food value. The protein content of oats, for instance, was increased with simazine by 28 percent over that of untreated oats. However, beans grown as a second crop on previously treated soil were observed to have a lower level of protein than a control. The carotene content of carrots was increased after treatment with linuron.

Under certain conditions, insect pests and plant pathogens have been found to increase after using herbicides. Although the examples given are relatively isolated and the relationships not fully understood, they indicate the desirability of more in-depth follow-up studies. Apparently some weed killers alter the chemical makeup of the crop plants, making them more susceptible to insects, which consequently become more abundant on the treated crop plants. For example, higher than recommended 2,4-D applications resulted in increased wireworm damage to wheat. In one report the number of grasshoppers on pasture plots treated with 2,4-D was approximately double that on check plots. It was not determined whether the increase resulted from nutrition or a change in plants or plant populations. Bean plants exposed to sublethal levels of 2,4-D increased aphid progeny production during a 10-day period from 139 to 764 per aphid. Rice stalk borer larvae grew nearly twice as large when larvae were fed rice treated with 2,4-D. Even so, 2,4-D has been used extensively for over 25 years without significant impact on nonweed crop pests.

In addition, insect pests may increase if the number of beneficial insect predators is reduced after using herbicides. Aphid infestations were reported on oats after the use of 2,4-D because fewer predaceous coccinellid beetles were present and active in the crop. The occasional adverse effects on beneficial insects are probably associated with the destruction of weed habitat.

Few quantitative studies have been made to ascertain the indirect effects of herbicides on the population sizes of nontarget organisms in a system. However, because of actual animal and plant interrelationships, we would expect the population sizes of nontarget species to be either increased or decreased after herbicide treatments. Some bird-population reductions may be attributed in part to the elimination of shrubby roadside habitats by herbicides. On the other hand, deer populations in some areas were increased by herbicide use. Unintentional responses reported have not been of such economic or ecological importance as to significantly affect the benefit-to-risk ratio of most established uses.

Pond ecology and production can be affected by herbicide use. For example, simazine applied experimentally to ponds controlled the weed *Potamogeton foliosus* and all filamentous forms of algae for almost 5 months. It also lowered the pH of the water and drastically changed the species composition of bottom-dwelling invertebrates. Residues persisted for at least a year. A number of herbicides, such as the sodium salt of dalapon, diquat, and the dipotassium and disodium salts of endothall, have shown a safe margin for toxicity to fish and fish-food organisms.

AGRICULTURAL AND OTHER APPLIED USES

In this section, the use for herbicides in forestry, orchards, small fruits, grazing lands, crops, industrial rights-of-way, and aquatic situations will be briefly summarized.

Forestry

Herbicides are one of many management tools available for improving or maintaining yields from commercial forest lands. The management of forests is an economic necessity. Cutting commercial trees leaves undesirable species that may remain dominant thereafter. The use of least disturbing practices tends to promote forest stability with minimum loss from erosion and nutrient leakage.

Herbicides provide one of the most selective methods of eliminating shrub or cull-tree species to enhance desirable forest growth. The beneficial effect of a herbicide is greater and more permanent than the effective life of the chemical residues. The effects on wildlife habitat—desirable or otherwise—depend on the original habitat condition.

In forestry, herbicides are generally applied from aircraft. Unless proper and rigid precautions are followed, it is difficult to control the subsequent movement of herbicides, and drift can seriously damage susceptible nontarget vegetation. Thus great care must be exercised to (1) use proper formulations; (2) leave unsprayed strips and buffer zones around streams and other water areas, susceptible crops, and populated areas; (3) avoid application immediately before a heavy rainfall; (4) avoid spraying when there is excessive wind or an atmospheric inversion; (5) use coarse sprays; and (6) fly as low as practical.

Grazing Lands

The primary purpose of weed and brush control is to change the predominant vegetative composition of the grazing site from undesirable to desirable species. Aerial spraying is an important means of application on the more extensively brush-infested ranges and pastures.

Because of the selectivity and slow action of some herbicides, the species of plants that are not killed increase in size and cover coincident with the death of unwanted species. Thus soil protection may be *more* continuous than with some alternatives like bulldozing, which leaves the land susceptible to erosion. Alternative mechanical methods are relatively nonselective, and affected areas usually must be reseeded. This reseeding may not always be successful because of lack of soil stability or shade from prior cover.

Brush control on grazing land results in more than just increased forage production. Additional benefits may include a reduction in the cost of caring for livestock, ease of livestock production, reduced wind and water erosion, and more groundwater production in some situations over a longer period of time.

Most residues resulting from herbicides used on grazing lands have relatively short persistence (1 to 12 months) in soils and dissipate rapidly from animal tissues.

Aquatic Situations

Although aquatic vegetation is essential to the aquatic environment, excessively large populations or masses of aquatic plants may become highly detrimental to other aquatic organisms and reduce the usefulness of water for many other purposes. In the Western States aquatic weeds are a problem in over 100,000 miles of irrigation canals, reducing water flow, plugging up equipment, and resulting in a serious loss of water. The control of undesirable aquatic vegetation is also essential in wildlife and fisheries management. In the inland waterways of the Southeastern United States aquatic plants interfere with navigation. There are few alternatives to the use of aquatic herbicides, and these alternatives may incur greater environmental risk than herbicide use.

Because the aquatic environment is complex and misuse of chemicals could be far reaching, users of aquatic herbicides should have adequate training and experience. Many states are now employing a permit system of use. Permits are issued locally by professional agriculturists, wildlife specialists, or other trained experts who have experience in the field. The application of herbicides in public waters should be limited to trained commercial applicators or qualified state employees.

Field and Vegetable Crops

Herbicides used on field crops account for 84 percent of all herbicides used in agriculture. Atrazine is the most widely used herbicide, and corn receives more herbicides (over 40 percent) than any other crop. Depending on weather, weed species, soils, and cropping systems for corn, either herbicidal control, mechanical control, or a combination of these practices may be more effective. For example, under wet conditions herbicides may be more effective than mechanical cultivation; but under dry conditions mechanical control may be more effective than herbicides. Unfortunately, we cannot predetermine these weather conditions. A combination of controls for weeds leads to increased use of early planted corn that utilizes the full growing season, and thus increases yields. Planting in the Corn Belt about May 1 with the long-growing varieties means that field conditions are normally wet and cool, and hence herbicidal weed control is needed in early spring.

Chemical weed control diminishes restraints on crop rotations and disturbance of soil; it allows adjustment of row spacing to that optimum for each crop and the use of mechanical harvesting; it also results in economy of labor. Both yields and quality are improved through reduced competition from weeds, and usually costs per unit of production are lowered. For example, in the last decade the amount of hoe labor for cotton production in certain areas of the United States was reduced from 48 to 13 man-hours per acre by the use of herbicides. The cost of labor for weeding strawberries decreased from as much as $200 to as little as $16 per acre where selective herbicides were used in combination with cultivation. Eliminating herbicide use in the absence of feasible alternatives would eliminate the economic production of small grains in much of the Pacific Northwest. Weeds would severely compete for limited moisture and plant food, and would interfere with harvest operations. In a North Dakota study it was found that an estimated annual loss of $175,000,000 would result from discontinuing the use of 2,4-D and MCPA in cereal grains and flax. These herbicides are the only feasible method now available for controlling wild mustard.

Depending on the weather, weeds, and labor availability, net economic returns may be highest in corn production employing herbicides, mechanical cultivation, or a combination for weed control. Weed-control costs in corn employing herbicides where two herbicides are used range from $10 to $14 per acre, whereas the cost of three mechanical cultivations may range from $4 to $6 per acre. Usually a combination of herbicides and mechanical cultivations results in higher corn yields than those obtained by either method alone, and net returns are also higher. In the Corn Belt, higher soybean yields were obtained using a combination of herbicides and cultivation than with cultivation alone.

Fruit and Nut Crops

The cost of hand labor to control unwanted vegetation has become almost prohibitive on a commercial scale. Mowing, tillage, and the use of herbicides in various combinations are currently used to eliminate weeds as competition and as secondary hosts for other pests. Control is particularly critical in establishing a new orchard. Increased growth and yields result from the use of herbicides as compared with the use of mechanical weed-control techniques alone. Some of these benefits result from less competition for water and nutrients and from rodent and insect control.

Industrial and Domestic Weed Control

Nonchemical weed-control methods like mowing are helpful at some industrial sites, but herbicides are best suited to most industrial situations. Vegetation is controlled to minimize fire hazard, prevent interference with the transmission of essential public utilities, permit right-of-way maintenance, improve ballast drainage, and ensure roadside visibility. Among the factors to consider when selecting the method or combination of methods employed are accessibility (including type of terrain), erosion potential, possible effects on animal life, relationship to water supplies, potential drift to nontarget plants, and economics.

Turf, the preferred cover in many industrial as well as home and recreational situations, is difficult to maintain satisfactorily by cultural means alone.

Benefits and Risks

The assessment of the benefits and risks entailed in the use of herbicides or any other similar agricultural management tool is highly complex. Since both an ample food supply and a viable agricultural environmental life system are necessary for human survival, man must carefully manage his environment to ensure adequate food production. Herbicides are management tools that bring about significant, intended environmental effects; however, any unintentional health or ecological risk should be examined.

No single factor accounts for the high productivity of farmlands in the United States. Cultural practices, fertilizers, varieties that are high yielding and disease resistant, and control of insect pests and weeds all contribute. In terms of modern agriculture and forestry, a major benefit from the use of herbicides is the decreased labor, power, and machinery costs for weed control. The ability to effectively control weeds in a timely manner increases the quality and yield of marketable crops. Hand labor for many crops is almost eliminated, and the released labor can be diverted to other productive work activities.

In making assessments, each particular weed-control situation must be evaluated on the basis of the best available knowledge of the economic, environmental, and health benefits and risks. This study presents evidence that (1) herbicide use increases the yield of many crops (in addition to this obvious food-production benefit, some land is released from cropping, which is a beneficial environmental impact); (2) herbicides used to control aquatic weeds may improve some lakes and pond environments used for recreation; and (3) herbicides have been effectively used in some cases to improve habitats.

As mentioned, associated with the intentional benefits of herbicide use are certain environmental risks:

1. Herbicide carryover residues have resulted in phytotoxic effects on susceptible plants, but generally residues do not seem to be building up in the air, water, and soil environment. Monitoring should be continued, however.

2. Herbicides in some instances may alter nutritive constituents of plants, such as proteins, vitamins, and related materials, but these changes have not resulted in significant effects on yield or quality of crops.

3. In limited experiments, nontarget plants and other organisms have been shown to be affected by herbicide exposure; therefore field experiments should be continued and expanded.

4. Based on minimal data, herbicide impact on natural ecosystems appears to be minor.

Weeds can be controlled by herbicides, by mechanical cultivation, by hand labor, or by a combination of practices. Which alternative is most efficacious depends on a spectrum of interacting variables for each particular situation, including crop rotation, soil, weather, weed species, terrain, and economics. Each weed-control situation should be evaluated on the basis of the best available knowledge of the benefits and risks to humans and the environment.

CHEMISTRY AND ANALYSIS

FINDINGS

1. *Currently used herbicides can be placed in one of 13 well-defined groups on the basis of chemical structure, with a few exceptions that fall into a miscellaneous group.*

2. *Proposed new herbicides can therefore be grouped, and one can be alerted to possible hazards associated with the group in question.*

3. *Tests applicable for groups in question should be conducted to prove or disprove the existence of problems.*

4. *Monitoring of herbicides should be continued to minimize the danger of contamination.*

5. *Nearly all herbicides are at least partially metabolized by some plant, animal, or soil-microbial system.*

6. *The factors that render many herbicides biodegradable are poorly understood.*

CHEMISTRY OF HERBICIDES

Introduction

Large-scale weed control by chemicals is a relatively recent development in agriculture. Prior to the 1940s, which is generally considered the beginning of the modern era of chemical weed control, certain inorganic salts were used as herbicides. In biblical times such herbicides as ashes, common salts, and bittern were used in agriculture. Due to the nonselective nature of these materials, one suspects that they were used sparingly for localized treatment and that cultivation was the major method of weed control.

An interesting history of weed control prior to the introduction of chemical herbicides has been prepared by Timmons (1970). The first selective action of an inorganic salt was demonstrated by Bonnet (1897) in France in 1896, who showed that copper sulfate controlled charlock [*Brassica kaber* (D.C.) L. C. Wheeler] in wheat. Many inorganic salts have been tried as herbicides including such compounds as ammonium thiocyanate (NH_4SCN), ammonium nitrate (NH_4NO_3), ammonium sulfate [$(NH_4)_2SO_4$], ferrous sulfate ($FeSO_4$), and copper sulfate ($CuSO_4$). The most widely used inorganic herbicides, however, were arsenate, borate, and chlorate, usually as the sodium salts. The two valence states of arsenic in pesticides are the trivalent form (As^{3+}), as in sodium arsenite, and the pentavalent form (As^{5+}), as in sodium arsenate.

Sodium arsenite has been widely used since about 1890 as a weed killer, particularly as a nonselective soil sterilant. Consequently, it found use around military and commercial installations along roadsides and on railroad rights-of-way. Since about 1925 sodium arsenite has been used rather extensively as an aquatic herbicide in lakes and farm ponds. From 1902 to 1937 it was used by the U.S. Army Corp of Engineers for controlling waterhyacinth in Louisiana. The use of sodium arsenite for controlling crabgrass (*Digstaria samquinalu*) expanded rapidly from only a few hundred tons in the early 1950s to 5000 tons in 1959, or about 17 percent of the total arsenic consumption in the United States that year. Due to its highly toxic nature (LD_{50} = 10 mg/kg), sodium arsenite has largely been displaced by the organic herbicides.

Borates are generally used for nonselective long-term weed control, in combination with other herbicides such as 2,4-D, TCA, ureas, and triazines. Sodium chlorate, like the borates, is used primarily as a soil sterilant and is applied at rates of 200 to 1000 lb/acre. It was first used for weed control in France in 1923 and in the United States from 1925 to 1930. Despite its rather high cost and serious fire hazard, its use expanded rapidly. Idaho used 4 million pounds from 1927 to 1935, and Kansas used nearly 3 million pounds from 1939 to 1940 (Timmons, 1970).

Two other inorganic herbicides of some significance are ammonium sulfamate and sulfuric acid. Ammonium sulfamate ($NH_4SO_3NH_2$) is a highly water soluble compound of low mammalian toxicity and has been used primarily for brush control since about 1940. Sulfuric acid (H_2SO_4) has been used since the turn of the century for controlling annual weeds. It was first used by the French for the control of annual forbs in cereals in 1911. By 1935 sulfuric acid was being used in the United States for weed control in onions (*Allium cepa* L.) and to some extent in cereals. Due to its corrosive nature, the use of sulfuric acid as a herbicide declined with the introduction of selective organic compounds.

Although the modern era of organic chemicals used as herbicides is generally attributed to the development of 2,4-D in the early 1940s, there are several examples of earlier successes with synthetic organic herbicides. Kögl *et al.*'s discovery in 1934 that indoleacetic acids promoted cell elongation in plants led to the synthesis and evaluation of many structurally related organic compounds. Two years prior to this discovery, 3,5-dinitro-*o*-cresol was introduced as a herbicide for weed control. Dinitrocresol (DNOC) had been used as an insecticide since 1928, but in 1932 the selective herbicidal action of this and related compounds was discovered. The discovery of the phenoxyalkanoic acid herbicides by Zimmerman and Hitchcock at the Boyce Thompson Institute in 1942 ushered in an era of tremendous growth of synthetic organic herbicides.

The phenomenal growth of the herbicide industry occurred primarily after 1950. By 1950 the number of herbicides available for public use had increased to about 25 from the 15 available in 1940. The subsequent growth and chronology of new herbicides since 1950 has been summarized by Timmons (1970) and is given in Table 1.

In recent years the introduction of new herbicides has been somewhat slowed due to the increasingly stringent requirements for additional information for registration. The best current estimates suggest that about 163 herbicides are registered in the United States. In 1970 approximately 391 million pounds of synthetic organic herbicides were produced domestically. This accounts for about 36 percent of all pesticides produced in the United States. Herbicide production grew at an average rate of 17 percent a year during the 5 years previous to 1970, compared to 8.7 percent for all pesticides. The formulated products in which these approximately 160 chemicals are utilized number in the thousands. For this reason, the common names of these 160 or more herbicides are used in the scientific literature.

Basis of Chemical Classification

The first prerequisite for a decision-making document is a classification system by which all the components can be analyzed. Herbicides may be grouped by various classification systems, such as those based on use patterns, time of application, crop selectivity, target plant, or chemical family. To the chemist the last classification represents the most logical and simplest system for grouping herbicides.

Table 1. CHRONOLOGY OF NEW HERBICIDES SINCE 1950[1]

Common name	Chemical name	Year of first public use
Monuron	3-(*p*-Chlorophenyl)-1,1-dimethylurea	1952
Endothall	7-Oxabicyclo[2.2.1]heptane-2,3-dicarboxylic acid	1953
Metham	Sodium methyldithiocarbamate	1953
MH	1,2-Dihydro-3,6-pyridazinedione	1953
Dalapon	2,2-Dichloropropionic acid	1954
Diuron	3-(3,4-Dichlorophenyl)-1,1-dimethylurea	1954
Silvex	2-(2,4,5-Trichlorophenoxy)propionic acid	1954
Amitrole	3-amino-*s*-triazole	1955
Erbon	2-(2,4,5-Trichlorophenoxy)ethyl 2,2-dichloropropionate	1955
Naptalam	*N*-1-Naphthylphtalamic acid	1955
CDAA	*N,N*-Diallyl-2-chloroacetamide	1956
Chlorpropham	Isopropyl-*m*-chlorocarbanilate	1956
DSMA	Disodium methanearsonate	1956
Monuron TCA	3-(*p*-Chlorophenyl)-1,1-dimethylurea mono (trichloroacetate)	1956
Sesone	2-(2,4-Dichlorophenoxy)ethyl sodium sulfate	1956
2,3,6-TBA	2,3,6-Trichlorobenzoic acid	1956
CDEC	2-Chloroallyl diethyldithiocarbamate	1957
Dazomet	Tetrahydro-3,5-dimethyl-2*H*-1,3,5-thiadiazine-2-thione	1957
EPTC	*S*-Ethyl dipropylthiocarbamate	1957
HCA	1,1,1,3,3,3-Hexachloro-2-propanone	1957
Neburon	1-Butyl-3-(3,4-dichlorophenyl)-1-methylurea	1957
PBA	Chlorinated benzoic acid	1957
Fenuron	1,1-Dimethyl-3-phenylurea	1958
Simazine	2-Chloro-4,6-bis(ethylamino)-*s*-triazine	1958
2,4-DB	4-(2,4-Dichlorophenoxy)butyric acid	1958
Atrazine	2-Chloro-4-ethylamino-6-isopropylamino-*s*-triazine	1959
DCPA	Dimethyl tetrachloroterephthalate	1959
Fenuron TCA	1,1-Dimethyl-3-phenylurea monotrichloroacetate	1959
Pebulate	*S*-Propyl butylethylthiocarbamate	1959
Prometone	2,4-Bis(isopropylamino)-6-methoxy-*s*-triazine	1959
Vernolate	*S*-Propyl dipropylthiocarbamate	1959
Acrolein	acrolein	1960
Amiben	3-Amino-2,5-dichlorobenzoic acid	1960
Diallate	*S*-(2,3-Dichloroallyl) diisopropylthiocarbamate	1960
Endothall[2]	7-Oxabicyclo[2.2.1]heptane-2,3-dicarboxylic acid	1960
Fenac	(2,3,6-Trichlorophenyl)acetic acid	1960
2,4-DEP	Tris[2-(2,4-dichlorophenoxy)ethyl] phosphite	1960
Amitrole-T	3-Amino-*s*-triazole + ammonium thiocyanate	1961
Barban	4-Chloro-2-butynyl *m*-chlorocarbanilate	1961
Cacodylic acid	Hydroxydimethylarsine oxide	1961
Propanil	3′,4′-Dichloropropionanilide	1961
Propazine	2-Chloro-4,6-bis(isopropylamino)-*s*-triazine	1961
Bensulide	*O,O*-Diisopropyl phosphorodithioate *S*-ester with *N*-(2-mercaptoethyl)benzenesulfonamide	1962
Dicamba	3,6-Dichloro-*o*-anisic acid	1962
Dichlobenil	2,6-Dichlorobenzonitrile	1962
Diquat	6,7-Dihydrodipyrido[1,2-*a*:2′,1′-*c*]pyrazinediium salts	1962

Table 1. CHRONOLOGY OF NEW HERBICIDES SINCE 1950[1] –Continued

Common name	Chemical name	Year of first public use
Isocil	5-Bromo-3-isopropyl-6-methyluracil	1962
Linuron	3-(3,4-Dichlorophenyl)-1-methoxy-1-methylurea	1962
Molinate	*S*-Ethyl hexahydro-1*H*-azepine-1-carbothioate	1962
––	Polychlorodicyclopentadiene isomers	1962
Triallate	*S*-(2,3,3-Trichloroallyl) diisopropylthiocarbamate	1962
Bromacil	5-Bromo-3-*sec*-butyl-6-methyluracil	1963
Butylate	*S*-Ethyl diisobutylthiocarbamate	1963
Diphenamid	*N,N*-Dimethyl-2,2-diphenylacetamide	1963
MSMA	Monosodium methanearsonate	1963
Picloram	4-Amino-3,5,6-trichloropicolinic acid	1963
Trifluralin	*a,a,a*-Trifluoro-2,6-dinitro-*N,N*-dipropyl-*p*-toluidine	1963
Ametryne	2-(Ethylamino)-4-(isopropylamino)-6-(methylthio)-*s*-triazine	1964
Cycloate	*S*-Ethyl N-ethylthiocyclohexanecarbamate	1964
Ioxynil	4-Hydroxy-3,5-diiodobenzonitrile	1964
Prometryne	2,4-Bis(isopropylamino)-6-(methylthio)-*s*-triazine	1964
Siduron	1-(2-Methylcyclohexyl)-3-phenylurea	1964
Bromoxynil	3,5-Dibromo-4-hydroxybenzonitrile	1965
Fluometuron	1,1-Dimethyl-3-(*a,a,a*-trifluoro-*m*-tolyl)urea	1965
Lenacil	3-Cyclohexyl-6,7-dihydro-1*H*-cyclopentapyrimidine-2,4(3*H*,5*H*)-dione	1965
Propachlor	2-Chloro-*N*-isopropylacetanilide	1965
Pyrazon	5-Amino-4-chloro-2-phenyl-3(2*H*)-pyridazinone	1965
Benefin	*N*-Butyl-*N*-ethyl-*a,a,a*-trifluoro-2,6-dinitro-*p*-toluidine	1966
Chloroxuron	3-(*p*-(*p*-Chlorophenoxy)phenyl]-1,1-dimethylurea	1966
Nitrofen	2,4-Dichlorophenyl *p*-nitrophenyl ether	1966
Paraquat	1,1′-Dimethyl-4,4′-bipyridinium salts	1966
Terbacil	3-*tert*-Butyl-5-chloro-6-methyluracil	1966
Metobromuron	3-(*p*-Bromophenyl)-1-methoxy-1-methylurea	1967
Nitralin	4-(Methylsulfonyl)-2,6-dinitro-*N,N*-dipropylaniline	1967
Karbutilate	*m*-(3,3-Dimethylureido)phenyl-*tert*-butylcarbamate	1968
Terbutryn	2-*tert*-Butylamino-4-ethylamino-6-methylthio-*s*-triazine	1969

[1] From Timmons (1970). See WSSA Handbook for current chemical nomenclature.
[2] For control of aquatic weeds.

In any decision-making process it is important to understand the basis for chemical classification and inferences that can be drawn due to similarities in chemical, physical, and biological properties. These similarities include starting materials, routes of synthesis, impurities, derivatives, methods of analysis, solubilities, persistence, mobilities, metabolites, and modes of action. A more detailed analysis of the chemistry of herbicides, particularly individual compounds in large families, will show certain dissimilarities. It is important to understand how these variations arise and the chemical basis for these dissimilarities.

Unfortunately, a few herbicides cannot be logically included in any chemical classification system. These include individual compounds like acrolein, amitrole, endothall, pyrazon, and picloram. An excellent source of information on the chemical, physical, and biological properties of many herbicides in current use is the *Herbicide Handbook* (1974) published by the Weed Science Society of America.

A classification of herbicides into 13 major groups is found in Table 2. This table is not all-inclusive, but is designed to group those compounds that are chemically related. A complete list of common and chemical names of the most recent list of herbicides published by the Weed Science Society of America, in alphabetical order, is found in the appendices.

Table 2. CLASSIFICATION OF HERBICIDES UNDER MAJOR CHEMICAL CLASSES

Group I: Chlorinated Phenoxyalkanoic Acids (1-14)

1	2,4-D	8	MCPB
2	2,4-DB	9	Mecoprop
3	2,4,5-T	10	Silvex
4	2,4,5-TB	11	Sesone
5	Dichloroprop	12	2,4-DEP
6	MCPA	13	2,4-DEB
7	Erbon	14	2,4,5-TES

Group II: S-Triazines (20-29)

15	Ametryne	23	Prometone
16	Atratone	24	Prometryne
17	Atrazine	25	Propazine
18	Chlorazine	26	Simazine
19	Cyanazine	27	Simetone
20	Cyprozine	28	Simetryne
21	Desmetryne	29	Trietazine
22	Ipazine		

Group III: Phenylureas (30-45)

30	Buturon	38	Linuron
31	Chlorbromuron	39	Metobromuron
32	Chloroxuron	40	Monolinuron
33	Cycluron	41	Monuron
34	DCU	42	Neburon
35	Diuron	43	Norea
36	Fenuron	44	Siduron
37	Fluometuron	45	Trimeturon

Group IV: Carbamates (49-50)

46	Barban	49	Propham
47	Chlorpropham	50	Swep
48	Dichlormate		

Table 2. CLASSIFICATION OF HERBICIDES UNDER MAJOR CHEMICAL CLASSES—Continued

Group V: Thiocarbamates (51-59)

51	Butylate	56	Pebulate
52	Cycloate	57	SMDC (metham)
53	CDEC	58	Triallate
54	Diallate	59	Vernolate
55	EPTC		

Group VI: Amides (60-67)

60	Alachlor	64	Naptalam
61	Butachlor	65	Propachlor
62	Cypromid	66	Propanil
63	Dicryl	67	Solan

Group VII: Chlorinated Aliphatic Acids (68-70)

68	TCA	70	Fenac
69	Dalapon		

Group VIII: Chlorinated Benzoic Acids (71-76)

71	Chloramben	74	Dichlobenil
72	DCPA	75	2,3,6-TBA
73	Dicamba	76	Tricamba

Group IX: Phenols (77-81)

77	Bromoxynil	80	PCP
78	DNOC	81	Ioxynil
79	Dinoseb		

Group X: Substituted Dinitroanilines (82-85)

82	Benefin	84	Nitralin
83	Dinitramine	85	Trifluralin

Group XI: Bipyridiniums (86-87)

86	Diquat	87	Paraquat

Group XII: Arsenicals (88-91)

88	MSMA	90	Cacodylic acid
89	DSMA	91	Sodium arsenite

Group XIII: Uracil Derivatives (92-94)

92	Bromacil	94	Terbacil
93	Isocil		

Examples of how the above classification system can be used in a decision-making process can be illustrated. The detection of dioxin (specifically, the 2,3,7,8-tetrachlorodibenzo-*p*-dioxin TCDD) in 2,4,5-T raised the question whether dioxin might be present in other herbicides. TCDD arises in the manufacturing process during the production of the trichlorophenol (Figure 1). Therefore it would be logical to examine herbicides in groups I and IX for dioxin contaminants. Since TCDD formation requires high-temperature hydrolysis and a chlorine atom in the 2-position on the ring, certain herbicides could be eliminated from groups I and IX. The chlorophenol in 2,4-D and related dichlorophenoxy herbicides is prepared by chlorination, i.e., no elevated temperatures are involved; therefore herbicides 1, 2, 5, 11, 12, and 13 could be eliminated in group I. Those herbicides lacking a chlorine atom in the 2-position would eliminate herbicides 6, 8, and 9 from group I and 77, 78, 79, and 81 from group IX. By the process of elimination one is left with those herbicides that are suspect for dioxin content. Woolson *et al.* (1972) analyzed approximately 129 samples of 17 different pesticides for TCDD content and found that 76 percent of the samples analyzed contained less than 0.1 ppm. The herbicides included in this survey were selected using the same rationale in formulating the above-mentioned classification system. As a safety measure, 2,4-D was included in the survey and, as predicted, was found to contain no TCDD.

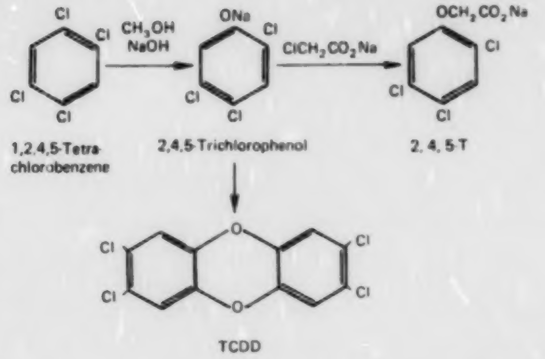


Figure 1. The formation of 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD) in the production of 2,4,5-T

Another example of the use of the chemical classification system in a decision-making process is illustrated by the azobenzenes. When propanil is added to soil in high concentrations, a number of azobenzene-type metabolites can be isolated (Bartha and Pramer, 1967; Linke and Bartha, 1970; and Plimmer and Kearney, 1970). Concern was expressed about the appearance of these azobenzenes in the environment, since they are structurally related to a known carcinogen, *p*-dimethylamino azobenzene. The principal azobenzene formed from propanil is 3,3′,4,4′-tetrachloroazobenzene (TCAB), which has subsequently been shown to be noncarcinogenic (Bartha and Pramer, 1970). Nevertheless, prior to the discovery of the noncarcinogenic properties of TCAB, it was important to know which herbicides might form azobenzenes. Propanil is first metabolized to 3,4-dichloroaniline, which subsequently undergoes condensation with a second molecule of 3,4-dichloroaniline to form TCAB (Figure 2). Therefore any herbicide metabolized to an aromatic amine might form azobenzenes.

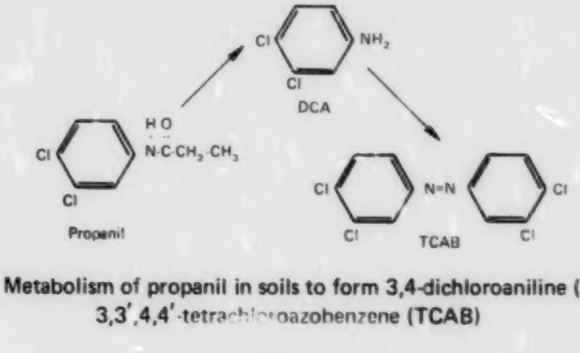


Figure 2. Metabolism of propanil in soils to form 3,4-dichloroaniline (DCA) and 3,3′,4,4′-tetrachloroazobenzene (TCAB)

Here again the chemical classification system played an important role in selecting those herbicides suspected of azobenzene formation. The aniline-based herbicides include the phenylureas (group III), carbamates (group IV), and some of the amides (group VI). Various herbicides in these groups have been examined for their potential to form azobenzenes. It was found that the phenylureas are not metabolized to azobenzenes (Dalton *et al.*, 1966) that certain steric factors in the herbicide molecule prevent azobenzene formation (Bartha *et al.*, 1968) and that azobenzene formation is a function of concentration in soils (Kearney and Plimmer, 1972). In many cases manufacturers have been required to submit information on azobenzenes resulting from the metabolism of existing or new aniline-based herbicides undergoing review for registration.

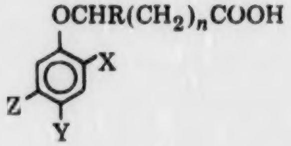
As environmental issues are raised about various herbicides, such as impurities (e.g., dioxins) or metabolites (e.g., azobenzenes), the chemical classification system offers a valuable tool for selecting related herbicides for examination and testing.

Chemical Properties of Herbicides

Herbicides are manufactured by synthesis from raw materials produced by the chemical industry. Chlorinated aromatic compounds are of major importance for the production of a wide variety of herbicidal compounds. Specifically, chlorinated phenols, chlorinated anilines, chlorinated benzoic acids, and nitroanilines are of major importance as starting points for herbicide syntheses. Non-aromatic compounds include chlorinated aliphatic acids, many heterocyclic derivatives (e.g., triazines), and several organometallic compounds.

The sections that follow deal with some of the physical properties of the major herbicide groups. Major topics discussed under each heading include synthesis, reactions, and current production estimates, if available.

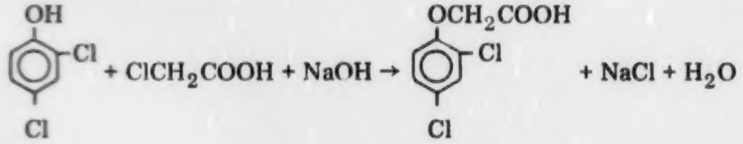
Group I: Chlorinated Phenoxyalkanoic Acids.—Herbicides in group I are derivatives of the structure shown below:



I

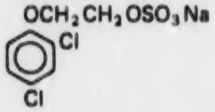
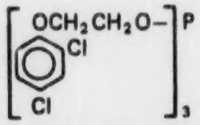
The names, formulas, and properties of the major chlorinated phenoxyalkanoic acid herbicides are found in Table 3.

The phenoxyalkanoic acids, particularly 2,4-D and 2,4,5-T, have maintained an important position in the herbicide market. The method of synthesis of 2,4-D is generally applicable to members of this class. Monochloroacetic acid is reacted with 2,4-dichlorophenol (II) in the presence of aqueous sodium hydroxide to from 2,4-D (III).



II III

Table 3. PROPERTIES OF SOME CHLORINATED PHENOXYALKANOIC ACID HERBICIDES[1]

Name	Formula[2]					Melting point (°C)	Solubility (ppm)[3]			
	R	X	Y	Z	*n*		Water	Acetone	Ethanol	Benzene
2,4-D[4]	H	Cl	Cl	H	0	140.5	0.07	45		1.07[5]
2,4-DB	H	Cl	Cl	H	2	117-119	46			
2,4,5-T	H	Cl	Cl	Cl	0	158	238		590	
2,4,5-TB	H	Cl	Cl	Cl	2	120-121				
Dichloroprop	CH_3	Cl	Cl	H	0	118	350	59.5		85[5]
MCPA[6]	H	CH_3	Cl	H	2	119	825		153[5]	
MCPB	H	CH_3	Cl	H	2	100	44			
Mecoprop	CH_3	CH_3	Cl	H	0	94-95	600			0.472[5]
Silvex[7]	CH_3	Cl	Cl	Cl	0	179-181	140	18		
Sesone[8]						170 (free acid) 245 (Na salt)	26.5	0.64		0.05[5]
2,4-DEP						200 (bp at 0.1 mm Hg)				

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[1] Adapted from Plimmer (1970).
[2] See formula I.
[3] Unless otherwise stated.
[4] U.S. Pat. 2,390,941 (1945), to American Chemical Paint Co.
[5] Grams per 100 grams of solvent.
[6] U.S. Pat. 2,740,810 (1956), to Diamond Alkali Co.
[7] U.S. Pat. 2,749,360 (1956), to the Dow Chemical Co.
[8] U.S. Pat. 2,573,769 (1951), to Union Carbide and Carbon Corp.

The phenoxyalkanoic acids are crystalline solids, soluble in organic solvents. The free acids, metal salts, amine salts, ammonium salts, or esters may be used as herbicides. Esters of 2,4-D or 2,4,5-T with *n*-butanol or alcohols of lower molecular weight are classed as "volatile" since their vapor has been shown to damage plants in close proximity to treated areas. Problems associated with volatilization can be avoided by esterifying phenoxyalkanoic acids with alcohols of higher molecular weight or alcohols that contain polar groupings such as polypropylene glycol or butoxyethanol.

The production of 2,4-D in 1970 was 44 million pounds, down 7.4 percent from 1969 (Fowler, 1972). The production, exports, and producers' domestic disappearance of 2,4-D and 2,4,5-T in the United States for 1960 to 1970 are shown in Table 4.

The estimated U.S. production of 2,4-D in 1971 was 45 million pounds of the active ingredient; 2,4,5-T production was estimated at 6 million pounds (Lawless *et al.*, 1972). The primary manufacturer of 2,4,5-T is the Dow Chemical Company at Midland, Michigan. Current specifications for 2,4,5-T production require a dioxin content (based on TCDD) of less than 0.1 ppm of the acid equivalent of 2,4,5-T, but the manufacturer has refined the synthetic process to make a product containing less than 0.1 ppm of TCDD.

Phenoxyalkanoic acids may be analyzed by a colorimetric method that involves reaction with chromotropic acid (4,5-dihydroxy-2,7-naphthalenedisulfonic acid) in concentrated sulfuric acid. In an improved procedure the phenoxy acids are cleaved by pyridine hydrochloride, and the liberated phenol is colorimetrically estimated after reaction with 4-aminoantipyrine in basic solution Conversion of free acid to the methyl ester by reaction with diazomethane or boron trifluoride in methanol gives a derivative suitable for analysis by electron-capture gas chromatography.

Table 4. PRODUCTION, EXPORTS, AND PRODUCERS' DOMESTIC DISAPPEARANCE OF 2,4-D AND 2,4,5-T IN THE UNITED STATES, 1960-1970[1]

Year	Production[2]		Exports[3,4]	Domestic disappearance[5]	
	2,4-D	2,4,5-T	2,4-D and 2,4,5-T	2,4-D	2,4,5-T
1960	36,185	6,337	8,796	31,131	5,859
1961	43,392	6,909	9,085	31,067	5,444
1962	42,997	8,369	10,192	35,903	8,102
1963	46,312	9,090	14,657	33,199	7,179
1964	53,714	11,434	13,037	43,986	8,912
1965	63,320	11,601	6,924	50,535	7,244
1966	68,182	15,489	5,419	63,903	17,080
1967	77,139	14,552	4,410	66,955	15,381
1968	79,263	17,530	3,391	68,404	15,804
1969	47,077	4,999	7,287	49,526	3,218
1970	43,576	(6)	9,571	46,942	4,871

[1] All values given in thousands of pounds.

[2] Source: U.S. Tariff Commission.

[3] Source: U.S. Bureau of the Census.

[4] Excludes military shipments abroad; these are not considered exports.

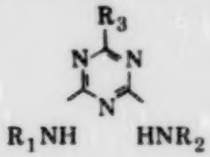
[5] Includes military shipments abroad.

[6] Separate figure not available.

The starting materials for 2,4-D production are 2,4-dichlorophenol and monochloroacetic acid. The former is manufactured by chlorination of phenol and the latter by chlorination of a mixture of acetic anhydride and acetic acid. Byproducts are the 2,6 isomer of dichlorophenol and higher chlorinated phenols that can be utilized for pentachlorophenol manufacture by further chlorination. Phenol itself can be obtained by basic hydrolysis of chlorobenzene, which is produced by direct chlorination of benzene. Thus benzene, acetic acid, acetic anhydride, chlorine, and sodium hydroxide suffice as raw materials for 2,4-D manufacture.

The production of 2,4,5-T is similar to that of 2,4-D except that 2,4,5-trichlorophenol is required as starting material and this is manufactured by the basic hydrolysis of 1,2,4,5-tetrachlorobenzene. Hydrolysis is carried out under pressure at an elevated temperature that must be carefully controlled to avoid formation of a toxic impurity, 2,3,7,8-tetrachlorodibenzo-*p*-dioxin. Tetrachlorobenzene is made by direct chlorination of benzene or may be obtained as a byproduct from the manufacture of benzene hexachloride.

Group II: *s*-Triazines.—Herbicides in group II are derivatives of the structure shown below:



IV

The names, formulas, and properties of the major *s*-triazine herbicides are given in Table 5.

Table 5. PROPERTIES OF *s*-TRIAZINE HERBICIDES[1]

Name	Formula[2]			Melting point (°C)	Solubility (ppm)					Vapor pressure at 20°C (mm Hg)
	R_1	R_2	R_3		Water	Acetone	Ethanol	Methanol	Benzene	
Ametryne[3]	C_2H_5	i-C_3H_7	SCH_3	84-86	185					8.14×10^{-7}
Atratone	C_2H_5	i-C_3H_7	OCH_3	94-96	70			18,000		3.0×10^{-7}
Atrazine[4]	C_2H_5	i-C_3H_7	Cl	173-175	70			18,000		
Simazine[5]	C_2H_5	C_2H_5	Cl	225-227	5			400		6.1×10^{-9}
Simetone[3]	C_2H_5	C_2H_5	OCH_3							
Simetryne	C_2H_5	C_2H_5	SCH_3							
Prometone[3]	i-C_3H_7	C_2H_5	OCH_3	91-92	730	>500,000			>250,000	2.3×10^{-6}
Prometryne[3]	i-C_3H_7	i-C_3H_7	SCH_3	118-120	48					1.0×10^{-6}
Propazine	i-C_3H_7	i-C_3H_7	Cl	212-214						2.9×10^{-8}
Lambast[6,7]	$NH(CH_2)$ → OCH_3[8] →		SCH_3	55	100	Very soluble	Slightly soluble		Very soluble	
Chlorazine[7]	$N(C_2H_5)_2$	$N(C_2H_5)_2$	Cl							

[1] Adapted from Plimmer (1970).
[2] See structure IV.
[3] U.S. Pat. 2,909,420 (1958), to J. R. Geigy Akt. Ges.
[4] U.S. Pat. 2,891,855 (1958), to J. R. Geigy Akt. Ges.
[5] Swiss Pat. 342,784 (1960), to J. R. Geigy Akt. Ges.
[6] Registered trademark Monsanto Co.
[7] Lambast and chlorazine have unsaturated rings.
[8] For R_1 and R_2.

The basic material for the production of *s*-triazine herbicides is cyanuric chloride, which is synthesized by trimerization of cyanogen chloride. Raw materials for the synthesis of cyanuric chloride are chlorine and hydrogen cyanide. Cyanuric chloride has three reactive chlorine atoms, which can be successively replaced by different functional groups. More vigorous reaction conditions are required for each successive replacement. The most important herbicides of this class have two alkylamino substituents and a chloro, methylthio, or methoxy group. Atrazine is obtained by the action of ethylamine and isopropylamine on cyanuric chloride. Reaction of atrazine with methylmercaptan gives ametryne. These are typical triazine herbicides, but in recent years *s*-triazine herbicides containing a variety of substituents have been developed.

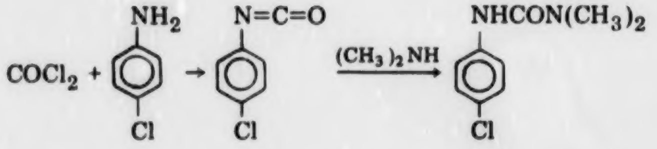
Triazine herbicides are colorless solids, only slightly soluble in water but quite soluble in organic solvents. Their vapor pressures are low (atrazine 3.0×10^{-7} mm Hg at 20°C), but small quantities may be lost by volatilization at ambient temperatures.

Generally the triazines are unreactive, and the alkylamino groups at the 4- and 6-positions do not react with normal acylating agents. Hydrolysis of the 2-chloro, 2-alkylthio, or 2-alkyloxy-4,6-bis(alkylamino)-*s*-triazines by acid or base gives the corresponding 2-hydroxy derivative. Hydrolysis provides a method for quantitative estimation of triazine by measurement of the absorbance at 225, 240, and 255 nanometers. The *s*-triazine ring is stable and is not cleaved except under drastic conditions.

The estimated U.S. production of atrazine in 1971 was 90 million pounds of the active ingredient (Lawless *et al.*, 1972). Atrazine is thus the leading herbicide in production. The production of simazine and propazine is estimated at 5 and 4 million pounds, respectively, during 1971. These three *s*-triazine herbicides are manufactured by Ciba-Geigy Chemicals. Atrazine is manufactured at the St. Gabriel plant in Louisiana.

Group III: Phenylureas.—Some important properties of group III herbicides are found in Table 6.

A typical synthesis proceeds by way of an isocyanate as intermediate. The isocyanate is synthesized by reaction of phosgene (V) with an aromatic amine (VI). The reaction of an isocyanate with an amine gives a urea, whereas reaction with an alcohol gives a carbamate. The chemistry of carbamates is discussed in a subsequent section. The synthesis of monuron is as follows:



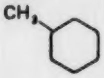
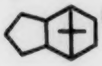
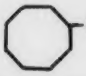
V VI Monuron

The reaction of chloroaniline in dioxane or other inert solvent with phosgene and anhydrous hydrogen chloride gives *p*-chlorophenyl isocyanate. Several methoxy ureas are used as herbicides, and these are prepared by using *O*-methylhydroxylamine in place of dimethylamine. The ureas are generally stable crystalline solids, soluble in organic solvents and slightly soluble in water. Basic hydrolysis of a urea regenerates the parent aromatic amine. This reaction forms the basis of an analytical method, since the free aromatic amine can be extracted into an organic solvent and estimated. Alternatively, the liberated aliphatic amine may be distilled and quantitatively absorbed in acid, which is then backtitrated.

The estimated production of diuron in the United States in 1971 was 6 million pounds of the active ingredient (Lawless *et al.*, 1972). Du Pont is the primary manufacturer of many phenylurea herbicides. In 1971, the estimated production of fluometuron (Ciba-Geigy), linuron (du Pont), and isorea (Hercules) was 4 million, 2 million, and 4 million pounds, respectively. The production of chlorbromuron, chloroxuron, fenuron, monuron, and siduron was less than 1 million pounds in each case.

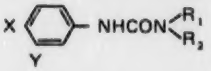
Group IV: Carbamates.—The names, formulas, and physical properties of several carbamate herbicides are given in Table 7.

Table 6. PROPERTIES OF PHENYLUREA HERBICIDES[1]

Name	Formula[2]				Melting point (°C)	Solubility (ppm)				Vapor pressure	
	X	Y	R_1	R_2		Water	Acetone	Ethanol	Benzene	°C	mm Hg
Fenuron[3]	H	H	CH_3	CH_3	133-134	3850				60	1.6×10^{-4}
Monuron[4]	Cl	H	CH_3	CH_3	174-175	230	52,000		2,900	25	5×10^{-7}
Diuron[4]	Cl	Cl	CH_3	CH_3	158-159	42	53,000		1,200	30	0.31×10^{-5}
					180-190 (decomposition)						
Fluometuron	H	CF_3	CH_3	CH_3	163-164	90	3			100	5×10^{-5}
Linuron	Cl	Cl	CH_3	OCH_3	93-94	75	500,000		150,000		
Metobromuron	Br	H	CH_3	OCH_3	95.5-96	330	Soluble	Soluble			
Monolinuron	Cl	H	CH_3	OCH_3		930				24	1.5×10^{-4}
Neburon[4]	Cl	Cl	CH_3	C_4H_9	102-103	4.8					
Siduron	H	H		H	133-138	18		160,000			
Chloroxuron	H	C_6H_4Cl	CH_3	CH_3	151-152	3.7					
Buturon	H	Cl	CH_3		145-146	30					
Chlorbromuron	Br	Cl	CH_3	OCH_3	94-96	50				20	4×10^{-7}
Norea	 NHCON$(CH_3)_2$				170-172	150	Soluble	Soluble			
Cycluron	 -NHCONH$(CH_3)_2$				138	1200					

[1] Adapted from Plimmer (1970).

[2] Refers to the following structure



[3] U.S. Pat. 2,655,447 (1953), to E. I. du Pont de Nemours & Co., Inc.

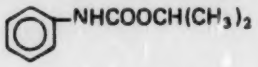
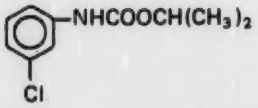
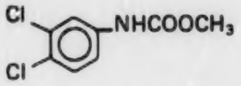
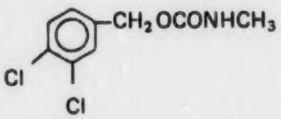
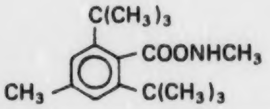
[4] U.S. Pat. 2,655,445 (1953), to E. I. du Pont de Nemours & Co., Inc.

The reaction described for the synthesis of a urea may also be used for the synthesis of a carbamate by using an alcohol instead of an aliphatic amine in the reaction with an isocyanate. Alternatively, the reaction of a chloroformate ester with a primary aromatic amine gives a urea.

Although the carbamates are crystalline solids, some of them are appreciably volatile; for example, propham volatilizes from the soil surface at field temperatures and must be incorporated at shallow soil depths to preserve its activity.

Hydrolysis of a carbamate by acid or base gives the aromatic amine, and this reaction can be used for analytical determination. Basic hydrolysis is preferable since acid hydrolysis is accompanied by decomposition and charring of the aromatic amine, and extractive separation is necessary before the free aromatic amine can be estimated.

Table 7. PROPERTIES OF SOME CARBAMATE HERBICIDES[1]

Name	Formula	Melting point (°C)	Solubility (ppm)[2]			
			Water	Acetone	Ethanol	Benzene
Propham (IPC)		87-88		Very soluble		
Chlorpropham (CIPC)[3]		38-40		Miscible	Very soluble	
Barban[4]	$C_6H_5NHCOOCH_2C{\equiv}CCH_2Cl$	75-76		0.0011[5]		37.0[5]
Swep		133-134				
Sirmate[6] UC 22463		52	170	Soluble		Soluble
Terbutol[7]		200	7			

[1] From Plimmer (1970).

[2] Unless otherwise indicated.

[3] U.S. Pat. 2,695,225 (1954), to Columbia Southern Chemical Corp.

[4] U.S. Pat. 2,906,614 (1959), to Spencer Chemical Co.

[5] Grams per 100 grams of solvent.

[6] Registered trademark, Union Carbide Co.

[7] U.S. Pat. 3,140,167 (1964), to Hercules Powder Co.; registered trademark.

The estimated U.S. production of chlorpropham in 1971 was 2 million pounds; the production of barban and terbutol was less than 1 million pounds each.

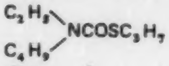
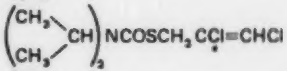
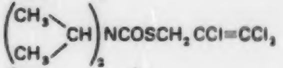
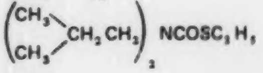
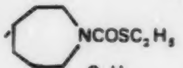
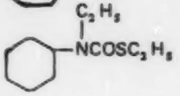
Group V: Thiocarbamates.—The names, formulas, and properties of some of the group V herbicides are found in Table 8.

The synthesis of *S*-ethyl dipropylthiocarbamate (EPTC) is typical of synthetic methods for the production of thiocarbamates; EPTC was first used as a herbicide in 1957.

The reaction of phosgene with di-*n*-propylamine (VII) gives a carbamoyl chloride (VIII), which subsequently reacts with a thiol (as the sodium derivative) to give the corresponding thiocarbamate (IX):

$$\underset{\text{VII}}{(n\text{-}C_3H_7)_2NH} + COCl_2 \rightarrow \underset{\text{VIII}}{(n\text{-}C_3H_7)_2NCOCl} + HCl$$

Table 8. PROPERTIES OF SOME THIOCARBAMATE HERBICIDES[1]

Name	Formula	Boiling point (°C)[2]	Solubility (ppm)[3]				Vapor pressure[3]	
			Water	Acetone	Ethanol	Benzene	°C	mm Hg
EPTC[4]	$(C_3H_7)_2NCOSC_2H_5$	127_{20}	375	Miscible		Very soluble	24	1.97×10^{-2}
SMDC[5]	$CH_3NHCSSNa\ 2H_2O$		72.2[6]					
Vernolate[4]	$(C_3H_7)_2NCOSC_3H_7$	140_{20}	109				24	5.4×10^{-3}
CDEC[7]	$(C_2H_5)_2NCSSCH_2CCl{=}CH_2$	$128\text{-}130_1$	92	Soluble		Soluble	200	2.2×10^{-3}
Pebulate[8]	 $(C_2H_5)(C_4H_9)NCOSC_3H_7$	142_{20}	30	Miscible	Miscible		25	4.8×10^{-3}
Diallate	 $((CH_3)_2CH)_2NCOSCH_2CCl{=}CHCl$	150_9	14	Miscible				
Triallate	 $((CH_3)_2CH)_2NCOSCH_2CCl{=}CCl_2$	148_9	4	Soluble	Soluble			
Butylate	 $((CH_3)_2CH_2CH_2)_2NCOSC_2H_5$	137.5_{21}						
Molinate		137_{10}	1000	Miscible				
Cycloate[9]		146_{10}						

[1] Adapted from Plimmer (1970).

[2] The subscripts give the pressure in millimeters of mercury.

[3] Unless otherwise indicated.

[4] U.S. Pat. 2,913,327 (1959), to Stauffer Chemical Co.

[5] U.S. Pat. 2,791,605 (1957), to Stauffer Chemical Co.

[6] Grams per 100 milliliters.

[7] U.S. Pat. 2,919,182 (1959), to Stauffer Chemical Co.

[8] U.S. Pat. 3,175,897 (1965), to Stauffer Chemical Co.

[9] U.S. Pat. 3,185,720 (1965), to Stauffer Chemical Co.

$$(n\text{-}C_3H_7)_2NCOCl + C_2H_5SNa \rightarrow (nC_3H_7)_2NCOSC_2H_5 + NaCl$$

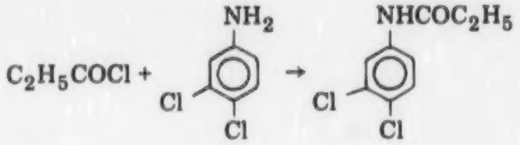
IX

Thiocarbamates are generally somewhat volatile; the vapor pressure of EPTC is 2×10^{-2} mm Hg at 24°C compared with 6×10^{-9} mm Hg for simazine. Losses from soil were found to be proportional to the vapor pressure of the thiocarbamate but may be influenced by formulation. Greater losses from wet soil as compared to dry have been ascribed to the binding or adsorption of the pesticide on dry soil. Soil moisture occupies adsorption sites in wetter soils, and the unadsorbed herbicide is lost by volatilization into the atmosphere.

Generally, acid hydrolysis of the thiocarbamates liberates free amine, which can be distilled from the reaction mixture after it has been made alkaline. Quantitative estimation of the thiocarbamate is based on the amount of amine produced, which is readily determined colorimetrically by reaction with cupric dithiocarbamate.

Group VI: Amides.—The names, formulas, and properties of several important amide herbicides are found in Table 9.

Aromatic amides may be synthesized by the reaction of an acid chloride with an amine. This synthetic pathway is utilized for the production of a number of substituted anilide herbicides, such as 3′,4′-dichloropropionanilide (propanil, X) used for weed control in rice.



X

The anilide herbicides may be hydrolyzed to the free aromatic amine which can be estimated colorimetrically after diazotization and coupling.

Several herbicides are synthesized from secondary amines, and these are generally chloroacetamide derivatives of the type $ClCH_2CONR_1R_2$, where R_1 is an alkyl group and R_2 an aromatic or an alkyl group. In the simplest case $R_1 = R_2 = C_2H_5$ (CDA). It has been suggested that such herbicides owe their effectiveness to their ability to react with enzymatic sulfhydryl groups in plants.

The estimated production and manufacturers of several important amide herbicides in the United States in 1971 are as follows: propachlor, 23 million pounds (Monsanto); alachlor, 20 million pounds (Monsanto); CDAA, 10 million pounds (Monsanto); propanil, 6 million pounds (Monsanto; Rohm & Haas); and diphenamid, 3 million pounds (Elanco and Upjohn) (Lawless *et al.*, 1972).

Groups VII and VIII: Chlorinated Aliphatic and Benzoic Acids.—Due to certain chemical similarities, the chlorinated acid herbicides are discussed together in this section. The names, formulas, and properties of the chlorinated aliphatic acid herbicides are found in Table 10.

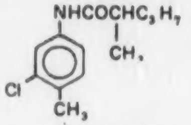
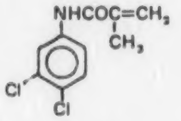
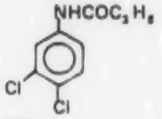
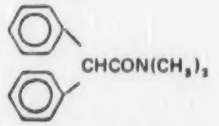
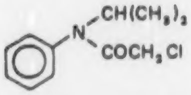
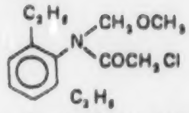
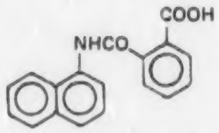
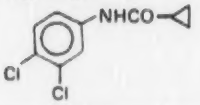
Herbicides of simple chemical structure are represented by chlorinated derivatives of aliphatic acids, such as trichloroacetic acid (TCA) and 2,2-dichloropropionic acid (dalapon). The acids are hydrolyzed in solution at room temperature, and, at physiological pH, a chlorine atom can be replaced by a hydroxyl group. Trichloroacetic acid breaks down in solution to form chloroform and carbon dioxide. Dry dalapon sodium salt is stable, but aqueous solutions are subject to decomposition, giving rise to pyruvic acid and a chloride ion. The Dow Chemical Company is the producer of dalapon and TCA, and an estimated 5 million pounds of dalapon as compared with less than 1 million pounds of TCA for herbicide use were produced in the United States in 1971 (Lawless *et al.*, 1972).

The names, formulas, and properties of the chlorinated benzoic acids are found in Table 11.

Chlorinated benzoic acids and their derivatives form a heterogeneous group of compounds, including 2,3,6-trichlorobenzoic acid, 3,6-dichloro-2-methoxybenzoic acid (dicamba), and a number of benzonitrile (cyanobenzene) derivatives. The derivatization of the acids by reaction with diazomethane or boron trifluoride/methanol gives methyl esters that are useful for gas-chromatographic analysis. The acids are generally high-melting-point solids and are moderately soluble in water, especially as salts.

Amiben (3-amino-2,5-dichlorobenzoic acid) is an aromatic amino acid of economic importance first registered in the United States in 1960. For its manufacture 2,5-dichlorobenzoic acid is

Table 9. PROPERTIES OF AMIDE HERBICIDES[1]

Name	Formula	Melting point (°C)	Solubility (g/100 g solvent)[2]				Vapor pressure	
			Water	Acetone	Ethanol	Benzene	°C	mm Hg
Solan[3]	 NHCOCHC$_3$H$_7$ CH$_3$ Cl CH$_3$	85-86	8-9[4]					
Dicryl	 NHCOC=CH$_2$ CH$_3$ Cl Cl	127-128	Insoluble	20				
Propanil	 NHCOC$_2$H$_5$ Cl Cl	93-94	500					
Diphenamid[5]		134-135	0.5[4]	15[4]				
Propachlor	 CH(CH$_3$)$_2$ N COCH$_2$Cl	67-76	700[4]	30.9		50	110	0.3
Alachlor	 C$_2$H$_5$ CH$_2$OCH$_3$ N COCH$_2$Cl C$_2$H$_5$	110[6]						
CDAA[7]	$CH_2ClCON(CH_2CH{=}CH_2)_2$	74[8]			50^{-1}[8]		20	9.4×10^{-3}
Naptalam (NPA)[9]		185	200	5000				
Cypromid		131	<0.01			3		

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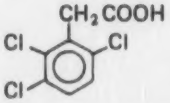
[1] Adapted from Plimmer (1970).
[2] Unless otherwise stated.
[3] U.S. Pat. 3,020,142 (1962), to F.M.C. Corp.
[4] Parts per million.
[5] U.S. Pat. 3,120,434 (1964), to Eli Lilly and Co.
[6] Boiling point at 0.03 mm Hg.
[7] U.S. Pat. 2,864,683 (1958), to Monsanto Chemical Co.
[8] Boiling point at 0.3 mm Hg.
[9] U.S. Pats. 2,556,664 and 2,556,664 (1951), to U.S. Rubber Co.

Table 10. PROPERTIES OF CHLORINATED ALIPHATIC ACID HERBICIDES[1]

Name	Formula	Melting point (°C)	Boiling point (°C)	Solubility (g/100 g solvent)		
				Water	Acetone	Benzene
TCA	CCl_3COOH	59	197.5[2]	1306	850	201
	CCl_3COONa			833	0.76	0.007
Dalapon[3]	CH_3CCl_2COOH		185-190	Very soluble		
	CH_3CCl_2COONa	193-194		502	0.014	0.002
Fenac[4,5]		159-160		Slightly soluble		

[1] Adapted from Plimmer (1970).
[2] Vapor pressure at 76.99°C, 5.0 mm Hg.
[3] U.S. Pat. 2,642,354 (1953), to the Dow Chemical Co.
[4] A mixture of isomers; data refer to the 2,3,6-trichloro isomer.
[5] U.S. Pat. 2,977,212 (1961), to Heyden Newport Chemical Corp.

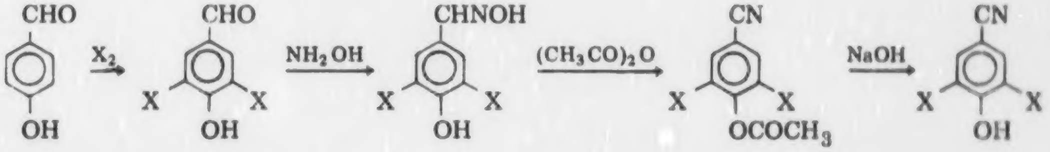
nitrated to yield 2,5-dichloro-3-nitrobenzoic acid. The nitro compound is then reduced to the 3-amino compound: isomeric nitro compounds must be removed by careful purification since they reduce the selectivity of amiben. Amiben may function as an acid or an aromatic amine. In aqueous solution amiben rapidly darkens on exposure to light, but it is quite stable in the solid state.

2,6-Dichlorobenzonitrile (dichlobenil) is made by the chlorination of 2,6-dichlorotoluene. Hydrolysis of the product to 2,6-dichlorobenzaldehyde is followed by conversion to the oxime, which on dehydration with acetic anhydride gives the nitrile. Dichlobenil is a crystalline, relatively volatile solid. Hydrolysis with base converts it to 2,6-dichlorobenzoic acid.

The estimated U.S. production of several chlorinated benzoic acids in 1971 was as follows: amiben, 20 million pounds (Amchem), dicamba, 6 million pounds (Velsicol), and DCPA, 2 million pounds (Diamond) (Lawless *et al.*, 1972).

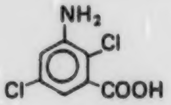
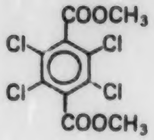
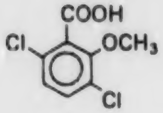
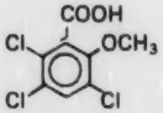
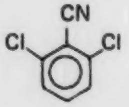
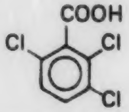
Group IX: Phenols.–The names, formulas, and properties of several phenolic herbicides are found in Table 12.

4-Cyano-2,6-dibromophenol (bromoxynil, XIa) and 4-cyano-2,6-diiodophenol (ioxynil, XIb) can be synthesized by the following reactions:



XI
a: X = Br
b: X = I

Table 11. PROPERTIES OF CHLORINATED BENZOIC ACIDS[1]

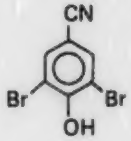
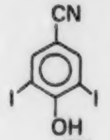
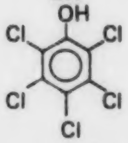
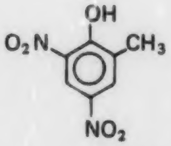
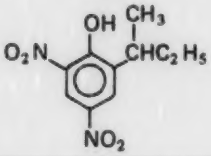
Name	Formula	Melting point (°C)	Solubility (g/100 g solvent)[2]				Vapor pressure	
			Water	Acetone	Ethanol	Benzene	°C	mm Hg
Amiben[3]		210	700[4]	23.27	17.28	200[4]		
DCPA[5]		156 (decomposes at 360-370)	<0.5[4]	10		25	40	0.01
Dicamba[6]		114-116	0.45		92.2		100	3.75×10^{-3}
Tricamba		139-139	Slightly soluble					
Dichlobenil[7]		139-145	18[4]				20	5.5×10^{-4}
2,3,6-TBA[8]		125-126	0.84	60.7		23.8		

[1] Adapted from Plimmer (1970).
[2] Unless otherwise stated.
[3] U.S. Pat. 3,014,063 (1958), to Amchem. Products Inc.
[4] Parts per million.
[5] U.S. Pat. 2,923,634 (1960), to Diamond Alkali Co.
[6] U.S. Pat. 3,013,054 (1961), to Velsicol Chemical Corp.
[7] U.S. Pat. 3,027,248 (1962), to North American Philips Co., Inc.
[8] U.S. Pat. 2,848,470 (1956), to Heyden Newport Chemical Corp.

PCP is manufactured by catalytic chlorination of phenol. Dinitrophenols are prepared by the controlled nitration of an alkylated phenol. Nitrophenols may present the hazard of explosion if completely dry. They form water-soluble salts of alkali metals and may be readily reduced to the monoamino nitro derivatives. They form typical molecular compounds with amines, hydrocarbons, and phenols. They are susceptible to decomposition by ultraviolet irradiation in alkaline solution. PCP decomposes in sunlight.

PCP may contain relatively large concentrations (<1000 ppm) of the higher chlorinated dioxins, that is, the hexa-, hepta, and octachlorodibenzo-*p*-dioxins (Woolson *et al.*, 1972). However, 2,3,7,8-tetrachlorodibenzo-*p*-dioxin was not detected in PCP. Studies are underway to reduce the dioxin

Table 12. PROPERTIES OF PHENOL HERBICIDES[1]

Name	Formula	Melting point (°C)	Solubility (g/100 g solvent)[2]				Vapor pressure	
			Water	Acetone	Methanol	Ethanol	°C	mm Hg
Bromoxynil		194-195	5[3]	17	9			
Ioxynil		212-213.5	50[3]	7	2			
PCP[4]		190-191	20-25[3]				100	0.12
DNOC		85.8	130[3]				25	105×10^{-6}
Dinoseb		38-42	0.0052			48	151	1.0

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[1] Adapted from Plimmer (1970).

[2] Unless otherwise stated.

[3] Parts per million.

[4] U.S. Pat. 2,131,259 (1938), to the Dow Chemical Co.

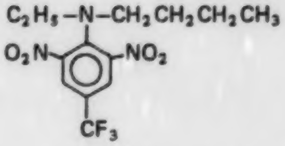
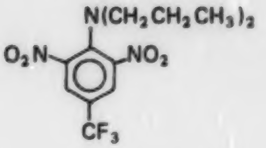
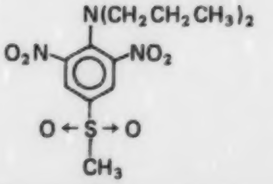
content of PCP, with a total content in the 100-ppm range. The hexa-, hepta-, and octachlorodibenzo-*p*-dioxins are considerably less toxic than the 2,3,7,8-tetrachloro isomer. The hexa isomer has been implicated as the factor responsible for chickedema.

Estimated U.S. production of PCP in 1972 as a herbicide, desiccant, molluscicide, and termite controller was 46 million pounds. The herbicidal production of dinoseb was 3 million pounds.

Group X: Dinitroanilines.—The names, formulas, and properties of several dinitroaniline herbicides are found in Table 13.

Dinitroaniline derivatives have been used since 1963, when the herbicidal use of α,α,α-trifluoro-2,6-dinitro-*N*,*N*-di-*n*-propyl-*p*-toluidine (trifluralin) was reported. This compound is typical of a number of related *N*-alkyl-2,6-dinitroaniline derivatives that have been developed in recent years. Synthesis depends on the formation of substituted 2,6-dinitrochlorobenzene (XII), which undergoes reaction with an amine to yield a substituted 2,6-dinitroaniline (XIII).

Table 13. PROPERTIES OF SUBSTITUTED DINITROANILINE HERBICIDES[1]

Name	Formula	Melting point (°C)	Boiling point (°C)[2]	Solubility in water (ppm)[3]	Vapor pressure	
					°C	mm Hg
Benefin		65-66.5	$121\text{-}122_{0.5}$ $148\text{-}149_{7}$	70^{25}	25	4×10^{-7}
Trifluralin		48.5-49	$96\text{-}97_{0.18}$	1^{27}	24.5	1.99×10^{-4}
Nitralin		151-152		0.6^{25}	25	1.5×10^{-6}

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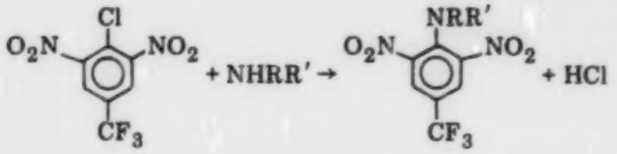
[1] Adapted from Plimmer (1970).
[2] The subscripts give the pressure in millimeters of mercury.
[3] All three compounds listed are soluble in acetone and slightly soluble in ethanol.



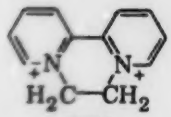
XII XIII

R and R' = alkyl

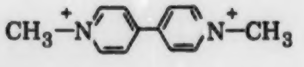
Dinitroaniline herbicides are bright-yellow or orange crystalline solids and are generally of low solubility in water. Trifluralin is slightly volatile and is also subject to photodecomposition. Therefore it is normally applied as a herbicide by incorporation in the soil. The alkyl groups can be removed by irradiation or by the action of enzymes.

Trifluralin production has increased steadily over the last 9 years, with an estimated U.S. production of 25 million pounds in 1971 (Lawless *et al.*, 1972). Nitralin production is estimated at 8 million pounds and that of benefin at less than 1 million pounds.

Group XI: Bipyridiniums.—The structures of diquat (1,1-ethylene-2,2'-bipyridinium, XIV) and paraquat (1,1'-dimethyl-4,4'-bipyridinium, XV) are shown below:



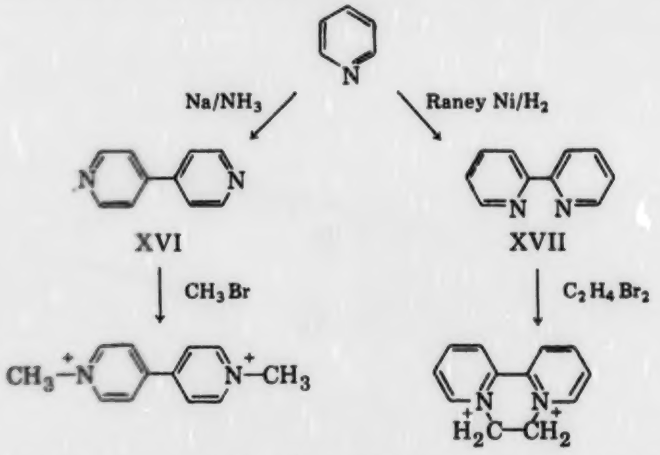
XIV



XV

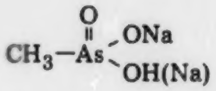
Paraquat melts at 175° to 180°C and is soluble in water but insoluble in organic solvents. Diquat melts at 335° to 340°C and decomposes at higher temperatures. It is very soluble in water and slightly soluble in acetone.

Bipyridinium herbicides are synthesized by the reduction of pyridine with sodium in liquid ammonia, which gives an ion radical that is oxidized to 4,4′-bipyridine (XVI), and quaternization with methyl bromide yields paraquat. Raney nickel reduction of pyridine gives 2,2′-bipyridine (XVII), which is quaternized with ethylene dibromide to give diquat.



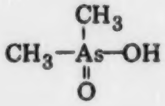
Imports of diquat and paraquat from Imperial Chemical Industries Ltd. (England) in 1969 were almost 750,000 and almost 3 million pounds, respectively (Lawless *et al.*, 1972).

Group XII: Arsenicals.—The structures of MSMA/DSMA (XVIII) and cacodylic acid (XIX) are shown below:



$$CH_3{-}\overset{\overset{\displaystyle O}{\|}}{As}\begin{smallmatrix}\diagup ONa\\ \diagdown OH(Na)\end{smallmatrix}$$

XVIII



$$CH_3{-}\underset{\underset{\displaystyle O}{\|}}{\overset{\overset{\displaystyle CH_3}{|}}{As}}{-}OH$$

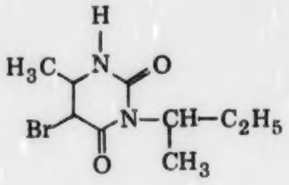
XIX

DSMA is the sodium salt of MSMA (methanearsonic acid). Cacodylic acid (hydroxydimethylarsine oxide) is also marketed as the sodium salt. MSMA is a white crystalline solid that melts at 132° to 139°C and is extremely soluble in water (25.6 percent by weight). Cacodylic acid is a colorless crystalline solid that melts at 200°C and is extremely soluble in water (66.7 percent by weight).

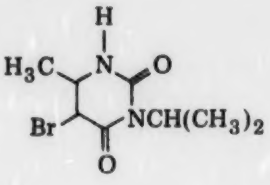
Methanearsonic acid is prepared commercially by reacting sodium arsenite with methyl chloride under pressure at 60°C. Cacodylic acid is prepared by reacting dimethylarsine trichloride [$(CH_3)_2AsCl_3$] with water.

Estimated U.S. production of MSMA/DSMA in 1971 was 35 million pounds (Lawless *et al.*, 1972). Production of cacodylic acid was approximately 2 million pounds.

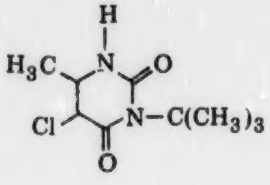
Group XIII: Uracil Derivatives.—The structures of 5-bromo-3-*sec*-butyl-6-methyluracil (bromacil, XX), 5-bromo-3-isopropyl-6-methyluracil (isocil, XXI), and 3-*tert*-butyl-5-chloro-6-methyluracil (terbacil, XXII) are shown below:



XX



XXI



XXII

Uracil derivatives are prepared by the condensation of acetoacetic acid with a substituted urea. The resulting methyl uracil is then halogenated. Some physical properties of the substituted uracils are found in Table 14.

Table 14. PROPERTIES OF URACIL HERBICIDES

Name	Molecular weight	Melting point (°C)	Solubility in water at 25°C (ppm)
Isocil	247.1	158-159	2150
Bromacil	261.1	158-159	815
Terbacil	216.7	175-177	710

Residues of the uracil derivatives in soils, water, and animals are measured by gas chromatography, using microcoulometric and electron-capture detectors with a sensitivity of 0.1 to 0.01 ppm.

Estimated U.S. production of bromacil and terbacil in 1971 was 8 million and 1 million pounds, respectively.

Contaminants

The contamination of herbicides can arise through a number of causes. The product of a synthetic chemical reaction in the laboratory or in an industrial plant is seldom a pure compound. The product, which may be referred to as a "technical" product, can contain appreciable amounts of other compounds also produced by the reaction of the raw materials in numerous side reactions. The contaminant may have undesirable properties. For example, 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD) may be found as a contaminant in 2,4,5-trichlorophenol, one of the starting materials for 2,4,5-T, if the reaction temperature is allowed to rise above an optimum value during the hydrolysis of 1,2,4,5-tetrachlorobenzene. TCDD is extremely toxic to mammals and birds, and its presence in quantities of a few parts per million is undesirable since its rate of degradation is slow. Samples of 2,4,5-T containing 27 ± 8 ppm TCDD were found to be teratogenic in rats and mice.

The herbicide 2,4-D may be contaminated with the isomeric 2,6-D (2,6-dichlorophenoxy-acetic acid) unless careful control of the process is maintained. 2,6-D is more resistant to biological degradation than is 2,4-D. Technical grade 2,4,5-T typically contains 90 to 92 percent 2,4,5-trichlorophenoxyacetic acid and 8 to 10 percent impurities. The detailed composition of technical material given by one producer was included in the Office of Science and Technology report on 2,4,5-T (1971). The impurities found in 2,4,5-T are shown in Table 15.

Table 15. IMPURITIES FOUND IN 2,4,5-T

Compound	Percent by weight
2,4,5-Trichlorophenoxyacetic acid	91.0 ± 1.0
2,4,5-Trichloroanisole	0.5 ± 0.1
5-Methoxy-2,4-dichlorophenoxyacetic acid	2.0 ± 0.5
2-Methoxy-4,5-dichlorophenoxyacetic acid	2.0 ± 0.5
2,4,5-Trichlorophenol	0.3 ± 0.1
Bis(2,4,5-trichlorophenoxyacetic acid)	3.0 ± 0.5
2,5-Dichlorophenoxyacetic acid	0.3 ± 0.1
Sulfate (SO_4)	0.2 ± 0.1
Sodium salt of 2,4,5-T	0.2 ± 0.1
Water	0.5 ± 0.2
Tetrachlorodibenz-*p*-dioxin (TDD)	<1 ppm

Other herbicides have been shown to contain contaminants that arise during manufacture; if these are phytotoxic or behave very differently from the parent in their toxicology, movement in soil, rate of microbial breakdown, or potential for bioaccumulation, further purification is usually necessary. Removal of such contaminants does not prevent the possibility of further contamination with other pesticides at the factory, at the formulating plant, or in storage. If two compounds are processed in the same plant, vapor contamination may occur. Some phenoxyalkanoic acid esters are sufficiently volatile to present serious problems if they are stored in the same area as other agricultural chemicals. The use of dirty equipment, improperly cleaned recycled drums, and improperly cleaned spray equipment are all further sources of cross-contamination. The cause of contamination must therefore be sought at every stage of pesticide manufacture, handling, and use.

Herbicide Metabolism

Metabolism involves the biological transformation of chemical entities through a variety of intermediate substances until one or more final end products are obtained. In the case of herbicides these end products may be carbon dioxide, water, and a chloride ion or a terminal residue of more complex and stable configuration. Nearly all herbicides are at least partially metabolized by some plant, animal, or soil-microbial system. Indeed, metabolism represents a major route of degradation for many herbicides. The factors that render a herbicide biodegradable are not well understood. Slightly water-soluble, highly chlorinated pesticides are generally most resistant to microbial attack. Many of the chlorinated hydrocarbon insecticides fall into this category. The introduction of such polar groups as $-OH$, $-NH_2$, $-CON<$, $-COO-$, and $-NO_2$, common to many herbicides, often affords biological systems a site of attack. Catalysts facilitating these reactions are all induced and constitutive cellular enzymes. As some organisms metabolize certain compounds only in the presence of other energy sources, the process of cometabolism is recognized as an important mechanism of metabolism for certain herbicides.

The principal reactions associated with the metabolism of herbicides include dealkylation, dehalogenation, amide or ester hydrolysis, oxidation, reduction, aromatic ring hydroxylation, ring cleavage, and condensate or conjugate formation. Many of these reactions, the enzymes, the pathways, and the intermediate products involved in herbicide metabolism have been investigated and described in some detail (Kearney and Kaufman, 1969).

Detoxication and excretion may be the ultimate results of some metabolic processes. The formation of glycosides and glucuronides by many organisms constitutes a mechanism for detoxication. The glycosides and glucuronides of herbicides are generally more water soluble than the parent herbicide molecule and are therefore more readily excretable by living organisms. Ultimate degradation of these conjugates may be accomplished by other organisms. At present, however, little is known about the subsequent fate of such compounds once they are liberated into the environment. Condensates are sometimes formed during the metabolism of some herbicides in soil, notably the aniline-based herbicides. The formation of these products, however, appears to be a function of the initial application rate. Excessively high application rates of these materials result in the formation of large amounts of the condensate-type compounds, whereas very little, if any, are formed at low or normal application rates.

Many organisms obtain energy for other life processes in the metabolism of chemicals. The initial metabolic reactions of many herbicides often require an expenditure of energy by the organism. Only when the herbicide is fragmented into compounds that can be channeled into oxidative cycles (e.g., the Krebs cycle) does the organism derive any useful energy. The complete oxidation of a chemical to carbon dioxide and water, although perhaps desirable from a "complete degradation" point of view, may be a wasteful process. Actually by a series of intermediate processes the energy originally incorporated into chemical bonds in herbicides may be transferred into ecologically acceptable products that can be used beneficially by many organisms when needed. Thus the overall trend in herbicide metabolism is toward less complex molecules. It follows that fragmentation of the pesticide molecule through metabolism generally results in detoxication and the formation of utilizable products. This is exemplified by the ultimate degradation of (1) 2,4-D to alanine and succinic acid, (2) dalapon to pyruvate and alanine, (3) dodine to creatine, and (4) TCA to serine. This represents the ultimate conversion of the pesticide to an ecologically acceptable metabolite.

Only in a few instances are the toxicological properties of one or more of a given herbicide's metabolites actually known. Although the general trend of herbicide metabolism is toward increasingly less toxic molecules, in some instances the toxicity of the metabolite may be equal to or greater than that of the parent pesticide molecule. Some pesticides, such as the herbicide sesone and probably 2,4-DEP, MCPES, 2,4-DEB, and 2,4-TES, are not biologically active themselves but actually require metabolic hydrolysis for activation to a phytotoxicant. In nearly all cases, however, even the more toxic metabolite is ultimately degradable to an ecologically acceptable entity.

The major emphasis in metabolic work has been to elucidate the pathway by which organisms convert metabolites to successively simpler and usually more polar products. The significance of these metabolites is a subject of considerable debate. If a metabolite is toxic or extremely persistent, or represents a major residue (e.g., more than 10 percent of the parent material), its distribution and impact on the environment should be ascertained.

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ANALYSIS OF HERBICIDES

Introduction

Herbicides are used to remove or prevent the growth of unwanted vegetation from areas where weeds compete with crops for nutrients, water, or light—or from areas where no vegetation is desired. Once the herbicide is applied, we are confronted with a residue situation. A small portion of the herbicide enters the air either during application or by the vaporization of surface residues. Some of the applied material falls onto the surrounding vegetation, but most of it falls onto or eventually reaches the soil. If the herbicide is applied near or over water, residues are probably present in the water. The concentrations of the residues decrease with time because of microbial activity, chemical degradation, dilution, and plant or animal metabolism.

It is important that we know the fate of these residues. Their persistence in soil determines whether further control is necessary and can also determine the choice of the next crop to be planted on the treated field. Residues in the air may be carried to other fields or may be inhaled by animals and humans. Residues in or on vegetation may be ingested by grazing animals or by consumers after harvest. Residues in the water may concentrate in marine animals, or, if the water is used for irrigation, the herbicide may adversely affect the irrigated crop.

Measurement of the residues in these substrates requires suitable methods of analysis. The methods must be accurate, to provide the most reliable data; they should be sensitive enough for measurement down to levels at which residues become insignificant; and they should be specific.

In applying these criteria to residue analysis, problems have been encountered. The analytical chemist assigned to devise a general method of analysis for herbicide residues is faced with a virtually impossible task. Over 100 compounds are used as herbicides, each with its own chemical characteristics. They range from completely ionic to nonionic types. This diversity of chemical properties makes it difficult to devise a general method of analysis applicable to all herbicides.

Over the years, methods of analysis have been developed for individual herbicides. This development was more or less dictated by federal regulations for the establishment of pesticide tolerances. The only requirements were a method that would determine residues of the herbicide in the treated crops and that could be used for the enforcement of any set tolerance. Specificity could be claimed by citing the agricultural registrations that eliminate the presence of similar herbicides on the crops of interest. Specificity might also be conferred by various forms of separation techniques in the method that limit the number of interfering compounds to a small number.

In a monitoring program it would exceed the manpower and funding resources of any laboratory to use these individual herbicide methods on every sample. Multiresidue methods are a "must" for monitoring, and the wider the applicability of the methods, the better. Development of multiresidue methods has been pursued mainly by governmental agencies. Progress has been slow because of the complexity of the problem, the lower priority of the problem in comparison with the more toxic insecticides, and the lack of manpower.

If a general herbicide procedure cannot be devised, the next approach is to develop general analytical methods for groups of related herbicides. Several such methods have already been reported. The method for chlorophenoxy acids and various acidic phenols has been used by the Food and Drug Administration in their total diet program (Yip, 1971). A similar method for these compounds is available for water analysis (Devine and Zweig, 1969). Methods for the determination of substituted ureas (Dalton and Pease, 1962; Katz, 1966; Baunok and Geissbuehler, 1968; McKone, 1969) and herbicidal carbamates (Onley and Yip, 1971) have been developed but have not been generally used because they are either too complex, too new, or unsuitable for the purpose. Procedures for *s*-triazines and dinitroanilines are in the testing stage.

The development of methods for the analysis of herbicide residues is further complicated by the tendency of herbicides and their metabolites to combine with plant or animal consitutents or soil particulates. It is entirely possible for the bulk of the residue in a sample to be in this combined form; if the method does not take this into account, the residue would pass undetected. Where this type of complexing is known to occur, hydrolysis steps have been introduced into the procedure to liberate the bound herbicide for determination as part of the residue.

The situation is further complicated by formation of new products resulting from the action of microorganisms or sunlight on the residue. Such products may be of greater toxicological significance than the parent compound, yet can go undetected because the method had not been designed to include them. If these products are in the soil, they can be absorbed by the plant root system and translocated throughout the plant, where again they can go undetected.

Current Methodology

Current residue methods usually consist of three parts: extraction, cleanup, and determination. Residues in soil, however, can also be demonstrated by growing plants susceptible to herbicides on the soil; by observing the degree of growth inhibition or growth distortion, the concentration of the residue can be estimated. Such bioassay methods can be sensitive to less than 0.1 ppm of residue in the soil, but they are not specific and it takes time to obtain an answer.

Chemical methods usually begin with an extraction step using either a polar or a nonpolar solvent. With soil samples and certain types of low-moisture foods, Soxhlet extraction is an efficient process for removing the residue. Water samples are usually extracted with a nonpolar solvent to separate the residue from the bulk of the sample. To determine very low residue levels (parts per billion), liter quantities may be required. Charcoal has been used to adsorb residues from water, after which the pesticides are recovered by extracting the charcoal. The efficiency of this adsorption and desorption process has not been established. The use of polyurethane-foam plugs has been suggested for the same purpose; although preliminary evidence seems to indicate that these plugs may be adequate, more supporting data are needed (Gesser *et al.*, 1972; Uthe *et al.*, 1972).

Soils, plants, and foods have been extracted by blending the sample with the extracting solvent. Nonpolar solvents will extract much of the waxes, fats, and oils along with the residue, thus necessitating rigorous cleanup steps. The efficiency of nonpolar solvent extractions is enhanced considerably if alcohol is also added to the sample. Polar solvents will also extract some plant materials, but their effectiveness has already been well documented.

These extraction procedures have been developed principally for the intact herbicides and some of their metabolites. The presence of residues bound to soil particles or to tissue constituents requires special treatment to liberate the residue before extraction. Such procedures have been devised for several herbicides but have not been adapted for any multiresidue method.

Herbicide residues in air are removed by forcing volumes of air through a scrubbing device. Through the use of impactors and impingers, the residues are trapped in a solvent from which they are eventually removed. The effectiveness of these devices is difficult to measure, and, until recovery data can be obtained, present data on residues in air may not be completely reliable. Interferences from other chemicals in the air may cause additional problems.

After an extract is obtained, the residue must usually be further purified, especially when the extract is highly colored or contains large amounts of fats and waxes. Extracts of water and air may not require further cleanup before the determinative step. For most samples, however, some type of cleanup is necessary.

Adsorption chromatography has consistently been applied for cleanup. In this technique the sample extract is adsorbed onto an activated adsorbent substance; then the residue is removed from the adsorbent by a system that favors its removal over that of the extraneous materials. Chromatography is usually accomplished on a column that has been packed with the adsorbent and the sample placed on top. Cleanup can also be done by thin-layer chromatography (TLC) using glass plates coated with the adsorbent and spotting the sample near the bottom edge, then developing the plate in an ascending direction with solvent. Areas of adsorbent on the plate are scraped off and washed to remove the residue for more definitive tests.

Such separation schemes are normally devised by using standards. Analysts should be aware of the pitfalls in using these schemes. The presence of extraneous materials in the extracts can modify the adsorbent or the partition coefficient sufficiently to change the elution rate or pattern by taking up many of the active sites on the adsorbent. It may be necessary to amend the analytical scheme to offset these effects. On samples containing large amounts of waxes and fats, it may be necessary to repeat the chromatographic cleanup step or to take a smaller sample for the initial cleanup and concentrate the residue to a volume suitable for the determinative step.

Current Instrumentation

Gas-liquid chromatography (GLC) continues to be the technique of choice for the rapid and efficient separation of herbicide residues from the sample. Coupled with a selective detection system, this technique is almost ideal for determining the concentration of the residue. Herbicides that can be analyzed by gas chromatography will pass through the chromatographic column at a speed governed by their distribution coefficients between the liquid and gas phases, by the temperature of the column, and by the rate of gas flow through the system. Each herbicide will elute from the column with a unique speed based on set operating conditions, which is why gas-liquid chromatography is such an excellent technique for multiresidue determinations.

Detectors impart to the gas chromatograph the requisite sensitivity and selectivity for residue work. Numerous types have been developed: electron capture, flame thermionic, flame photometric, microcoulometric, electrolytic conductivity, and mass spectrometric. Each detector has a useful function in herbicide analysis. Some can detect extremely small amounts (picogram) of residue but lack specificity. Others are specific but lack sensitivity. Flame-photometric detection is both specific and sensitive for phosphorus compounds. Electrolytic conductivity detection can be made both sensitive and specific for nitrogen. Regardless of which detector is used, the analyst should know the limitations of the detector used.

Despite improvements in instrumentation, gas-liquid chromatography is still somewhat of an art. The properties of a column are not constant; performance will gradually change as samples are continually introduced. The interpretation of the results requires a certain degree of judgment on the part of the analyst. Experience will enable the analyst to assess the significance of a peak in comparison to the noise level, the presence of other peaks, and the chemistry of the analytical procedure—and to suggest alternative procedures to answer the questions of quantity and identity. That a gas-liquid-chromatography peak of an unknown residue has the same retention time as that of a known standard does not necessarily mean that the two are the same. Retention time alone is not unequivocal proof of identity.

The electron-capture or affinity detector is the most widely used, not only because it is capable of detecting picloram amounts but also because it is stable and easy to use. It is not a completely specific detector, and the response is dependent on the number of electronegative groups on the molecule and the molecular configuration.

The flame-ionization detector is widely used in areas other than pesticide analysis. It is a general, nonspecific type of detector responding to carbon. This response makes it useful for detecting herbicide metabolites of unknown structure. If, however, an alkali salt is placed in the vicinity of the flame, response is enhanced for compounds containing phosphorus and nitrogen (Ives and Giuffrida, 1967; Tindle *et al.*, 1968). This detector has been used for *s*-triazines and carbamates. If a photometric cell is placed at right angles to the flame, compounds containing phosphorus and sulfur can be selectively detected by choosing the proper wavelength through the use of filters (Beroza and Bowman, 1968).

Microcoulometry has also been used as a selective detector for gas-liquid chromatography. Organic compounds eluting from the column are combusted under oxidative or reductive conditions to inorganic fragments, which then enter a halogen cell, a sulfur cell, or a nitrogen cell for quantitation. Interposition of suitable scrubbers between the combustion unit and the cells imparts greater specificity to these detectors. In many cases these detectors are the only ones that will provide the analyst with an answer for samples with abnormally high backgrounds. The chief problems associated with microcoulometric detectors are those of maintenance, inadequate sensitivity, and stability.

The electrolytic conductivity detector is used for compounds containing halogens, sulfur, or nitrogen (Coulson, 1966). As in the microcoulometric system, the compounds must be combusted before entering the detector. Scrubbers between the combustion unit and the detector are also necessary to make the detector specific for nitrogen compounds. The detector does offer stability and sufficient sensitivity for residue work.

A gas-liquid chromatograph interfaced with a mass spectrometer as the detector provides a very powerful tool for analysis. The success of this interfacing has been a major achievement because the residue must be separated from a large volume of carrier gas. Of all detectors, this one alone may provide sufficient proof to establish the nature of the residue. It is especially useful for identifying pesticide metabolites and alteration products. Cost is still a major barrier, and maintenance is a problem.

In instances in which gas-liquid chromatography cannot be used, colorimetric methods have been successfully applied. The general availability of spectrophotometers enables these methods to be used in most laboratories. Spectrophotometric methods using ultraviolet or infrared have been used mostly in formulation analysis. For residue work, such techniques have been hampered by lack of sensitivity, although micro infrared techniques have been used for qualitative purposes.

The use of colorimetric procedures in monitoring programs presents problems of specificity and sensitivity. These procedures are based on the reaction of a functional group in the molecule.

If several herbicides share an identical functional group, all will respond alike. This problem can be minimized if agreement can be reached that the resultant absorbance readings can be reported as a function of a single herbicide. In the case of diuron, a substituted urea herbicide, it has been shown that residues consist of diuron plus several metabolites. The moiety 3,4-dichloroaniline is common to diuron and its metabolites. It can be determined colorimetrically after diazotization and conjugation with an appropriate nucleophilic reagent. The amount of 3,4-dichloroaniline found is then calculated in terms of diuron.

Such a method cannot be used to monitor samples because 3,4-dichloroaniline is a moiety common to several urea herbicides, carbamate herbicides, and fungicides. This illustrates the need for a more specific method. An acceptable solution would be to use the colorimetric method for quantitative purposes and to use another method to identify the residue. This is feasible if only one herbicide is present, not a mixture.

Other instrumental methods, such as polarography or atomic absorption, have not been used extensively in herbicide-residue work. Polarography is a sensitive and specific tool, and it certainly should be more widely applied. Atomic absorption could be useful for determining arsenical and mercuric herbicides without regard to their molecular structures.

Specificity and Sensitivity Needs

The specificity of the methods in use today ranges from extremely specific, such as mass spectrometry, to quite nonspecific, such as colorimetry. Specificity is a desirable property of any method, especially in the area of pesticide analysis. Residue work deals with concentrations smaller than parts per million, and it is imperative that we be certain of our findings so that we can accurately report the identity and quantity of the residue. A method that is specific enables the analyst to say with complete confidence that the residue found could only be one particular compound. Most methods do not achieve this degree of confidence because of certain limitations in their means of detection. Halogen detectors are applicable to many herbicides with a little interference from natural contaminants. We are thus faced with a dilemma. On the one hand, we want a method that is applicable to a wide range of herbicides, but, on the other hand, the method should also be specific.

Tolerances are established on foods and water to ensure the safety of these products for consumption. Tolerance levels of 0.05 ppm are commonly promulgated. To detect such low levels of residues, sensitive methods must be devised. Through improvements in technology, the sensitivity of analytical methods is increasing, so that what once was considered a zero residue is now recognized as a finite one. Where formerly we would report zero residues, we can now find traces of a herbicide. At this stage we must fully evaluate the significance of these ultralow residues and decide whether we should strive for still greater sensitivity or cease further efforts in this direction and devote our energies toward trying to make the methods more specific.

Confirmation and Methodology

A peak on a gas chromatogram, a spot on a thin-layer-chromatography plate, or a positive color reaction does not guarantee the presence of herbicide residue. It is especially important in cases of samples with unknown spray history that a suspected residue be confirmed by other means. Confirmation at the residue level can be as difficult as the determination itself. Further cleanup of the sample may be necessary for some confirmatory methods.

An excellent means of confirmation is to analyze the sample by another procedure completely different in principle from the first. If the same results are obtained by the second method, confirmation has been achieved. This means of confirmation is the primary one if sufficient time and manpower are available.

If time and manpower are limited, other methods that do not require the extraction of a duplicate sample may be used. Pyrolytic gas-liquid chromatography is a relatively new technique, and instrumentation has recently appeared on the market to exploit its usefulness. This type of chromatography depends on the pyrolysis of the pesticide under strictly controlled conditions to produce a unique series of compounds, which are then chromatographed to obtain a pattern. Ideally, each pesticide will produce a unique pattern for unequivocal identification. Pyrolytic conditions can be adjusted toward this goal.

In the case of many pesticides, P-values may be used for qualitative identification (Beroza and Bowman, 1965; Bowman and Beroza, 1965). Because a P-value represents the distribution of a herbicide between two immiscible phases, several values can be obtained on a single compound by using a series of solvent pairs. By comparing the residue's P-values with those of a standard, an analyst can be quite accurate in identifying the residue. The presence of extraneous matter does not seem to alter the P-values too drastically from those obtained with a standard. This technique can only be as accurate as the method used for measuring concentrations of the pesticide in one phase of the solvent pair.

Derivatization is a technique used to convert one compound into another for ease of determination or detection. The phenoxyacid herbicides are usually converted to volatile methyl esters for determination by gas-liquid chromatography. The identity of these herbicides has been confirmed by a transesterification procedure in which the methyl esters are converted to corresponding *n*-propyl esters and rechromatographed (Yip, 1971); the recorder shows the disappearance of the methyl ester peak and the appearance of a new peak for the propyl ester.

Derivatives of aromatic-amine-based herbicides are prepared after a hydrolysis step to liberate the amine. The amine is diazotized and complexed; the different amines form azobenzenes having characteristic colors. This reaction has been used extensively in detecting substituted urea herbicides on thin-layer plates (Onley and Yip, 1969).

Thin-layer chromatography, like gas-liquid chromatography, has been used for several purposes: cleanup of samples, estimation of residue concentrations, and identification of compounds by their R_f values. The cleanup of samples is particularly important because extraneous material tends to impede the mobility of compounds. Too much material can result in streaks that mask the presence of the herbicide. In lieu of additional cleanup, it may be possible to use another thin-layer system that can give the desired separation. Another possibility is to chromatograph the sample, scrape off the area corresponding to the R_f value of the herbicide, and then rechromatograph it on another plate.

In the analysis of samples, the residue concentration can be estimated by comparing the density of the residue spot with that of standard spots. This requires the application of several levels of the standard herbicide to the thin-layer plate along with the sample in order to obtain a range of densities. The technique is only semiquantitative, but it may be sufficient to indicate whether a sample meets the tolerance level or to indicate absence of residue.

The R_f values are used to identify compounds on thin-layer plates. Additional specificity can be gained by using specific colorimetric methods for detecting the compounds on the thin-layer plate. This technique can provide both R_f and colorimetric reaction criteria for identification.

Two-dimensional thin-layer chromatography can also be used for identification. First the plate is developed in one direction; after drying, it is turned 90 degrees and developed again with a different solvent. Very uniform plates are required for this technique because otherwise solvent fronts will not be straight. Only one sample can be analyzed on a plate.

Retention times on two different gas-liquid-chromatography columns have been used as sufficient evidence for confirmation of a residue. The analyst should not depend on this method of confirmation as final. A better procedure is to use a different detector on the second gas chromatograph, preferably one that is more specific. This has been done with the herbicidal carbamates: compounds containing nitrogen were confirmed by the flame-thermionic detector, compounds containing sulfur by the flame-photometric detector, and halogenated compounds by electron capture (Onley and Yip, 1971).

Current Outlook

One of the biggest problems in pesticide-residue analysis is the inability of laboratories to confirm each other's results. Although the methods are designed to detect extremely minute quantities, in view of the type of sophisticated instrumentation that is available reproducibility between laboratories leaves much to be desired. Procedures published in the literature often do not provide enough details to allow a reader to execute the procedure with comparable results. Validated methods should be available and used if reliable data are to be obtained.

To increase reproducibility between laboratories, a quality-assurance program should be implemented among participating laboratories. A sample fortified with a known pesticide should be sent periodically to each laboratory to be analyzed as a regular pesticide sample. Results and all the raw data should be collected and evaluated. Laboratories not meeting the analytical requirements should be notified, and corrective action should be taken.

Our present capability for measuring residues in soil, water, plants, and air cannot be stated simply, because many factors enter into the final result. Sensitivity depends on the method of detection, the compound being measured, and the complexity of the sample containing the residue. If the analyst knows which herbicide to isolate and measure, his capability for measuring residues increases manyfold. In general, we can reliably measure 1 ppb in water, 0.1 ppm in soil and foods, and 0.1 $\mu g/ft^3$ of air.

Gas chromatography has afforded the chemist a most sensitive means of making an analytical determination. Under the proper conditions, picogram amounts can be measured. In providing this extreme sensitivity, gas chromatography also generated new problems. Solvents and reagents used in the analytical procedures must be ultrapure in order not to introduce materials that will cause a detector response. Entire new industries have arisen just for the purpose of purifying solvents for pesticide-residue analysis. A reagent blank should be obtained as a check on the reagents for each procedure that is used in the laboratory. This step alone can sometimes save a laboratory from reporting erroneous results.

Monitoring programs have been and are still being conducted by federal and state organizations. In these programs, pesticide contents in foods, in the environment, in wildlife, and in humans are determined periodically. Residues of chlorinated and organophosphorus insecticides are usually reported because methods of analysis are generally available. The herbicides included in these programs have been limited to the more widely used chlorophenoxy acids. Except for a few other individual herbicides, residue data for this class of pesticides in the monitoring programs have been minimal. It is hoped that more data will be forthcoming as additional herbicide-multiresidue methods are developed and put to use.

For the future, automation of analysis should provide an impetus for the accumulation of residue data. Thin-layer chromatography has been automated, and several automatic gas-chromatographic units are already on the market. Automatic sampling and extracting instruments are also available. Through additional refinements, it should not be too long before residue analysis becomes completely automated.

Liquid chromatography is the latest technique that has been introduced to analytical laboratories. The method provides rapid sample cleanup, as well as separation of similar types of compound, by using high-pressure systems. Major emphasis is being placed on devising resins suitable for high-pressure work. Applications of this technique to herbicide programs will increase as more instruments become available and successful results are obtained. Cleanup of samples remains the biggest problem in residue analysis, and if liquid chromatography can help solve this problem, its use will be adopted.

Analysis for herbicide residues is a difficult task because of the nature of these compounds. Although residues are not expected to be found from a majority of the registered uses of herbicides, there should be some data to show complete absence or presence at less than the tolerance level of any residue in soil, food, water, and air. Until we do have such information, we should not relax our efforts to obtain it.

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ENVIRONMENTAL EFFECTS

FINDINGS

An ample food supply and a viable environmental life system are both necessary for human survival. Man manages his environment for food production. Herbicides are one of the management tools that bring about significant, intended environmental effects. The purpose of this analysis is to investigate and evaluate the unintentional ecological effects that may result from herbicide use. It is important for man to know how herbicide use affects his environmental life system because man depends on the immense variety of species in the life system for maintenance of a quality atmosphere, for pollination, as well as for the biological degradation of pollution wastes.

After careful consideration of the available evidence, the following are our principal findings:

1. *Herbicide-treated areas in the United States represent about 6 percent of the total land area.* Of the total of nearly 500 million pounds of herbicides applied in the United States, 85.2 percent is applied to crop areas, 14.6 percent to rights-of-way and similar brush and tree areas, and 0.2 percent in aquatic locations.

2. *Herbicides increase the yields of crops, and this benefits our environment by releasing some land from cropping.* As much as 2.3 million cropland acres may be released from crop production because of herbicide use to control weeds.

3. *Some lakes and pond environments used for recreation may benefit from the use of herbicides to control aquatic weeds.*

4. *Herbicides have been used effectively in some cases to improve habitats.* Herbicides are sometimes used in terrestrial habitats to increase the food-carrying capacity for individual game species such as deer and grouse. Herbicides have also been used to improve some aquatic habitats for certain game birds and fish.

5. *The prime sources of herbicide pollution are drift during application and volatilization and runoff after application.* A significant portion of all agricultural herbicides are applied from aircraft. Of major concern is the fact that as much as 70 to 75 percent of the spray dispersed by aircraft under adverse conditions may never reach the target weeds. In addition, after application some herbicides vaporize rapidly and may drift and damage sensitive nontarget plants in the near vicinity.

6. *Residues of the herbicides reviewed do not seem to build up in the air, water, and soil environments.* Fortunately, the chemical and physical characteristics of herbicides cause most of them to degrade within about 3 months. A few herbicides bioconcentrate in aquatic organisms, but the concentration is seldom more than tenfold. Levels in warm-blooded animals are usually below detectable limits.

7. *Herbicides may cause physiological changes in plants, which in turn could upset the ecological relationships between these plants and animals associated with them.* Several herbicides increase toxic substances, such as potassium nitrate, produced by plants, making the plants poisonous to animals ingesting them. Also, herbicides can alter nutritive constituents of plants such as proteins and vitamins. The limited data available suggest that such changes have produced only minor problems.

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8. *Outbreaks of new pests may occur on crops treated with herbicides, thus requiring the use of additional pesticides.* Pathogen and insect pest problems caused by herbicides appear to be relatively infrequent; however, little study has been made of the problem. Some pests have been found to have increased growth and reproduction on crop plants treated with herbicides. In addition, some beneficial predaceous insects are destroyed by herbicides, and once this natural control is removed, the pest insects increase. After herbicide treatments, the physiology of some crop plants has changed, lowering the level of resistance to pathogen and insect pest attack.

9. *Predicting the impact of herbicides on a particular species is difficult because organisms differ in their sensitivity to herbicides.* Present data concerning the toxic effects of herbicides on plant and animal species and ecosystems are insufficient to predict the changes that will occur in natural ecosystems. With current use patterns, most herbicides degrade rapidly, with little or no bioconcentration in the life system. Hence, on the basis of limited data, herbicide impact on natural ecosystems appears minor.

10. *Little information is available concerning low-level, long-term, chronic effects of herbicides on nontarget species.*

11. *Although effective mechanical controls can be substituted for herbicides in weed management for many crops, herbicides are essential for the commercial production of some crops.* Weeds in most situations can be effectively controlled by mechanical cultivation; however, mechanical control may be more time consuming and costly, and hand labor is often unavailable.

12. *The use of herbicides for weed control in crops is sometimes not economically justified.* Using corn as an example and depending on the weather, weeds, and labor availability, economic returns may be highest from the use of herbicides, from mechanical cultivation, or from a combination for weed control. Often a combination of weed controls gives the best economic returns.

13. *The use of herbicides in some crops may interfere with normal crop rotation, resulting in increase in pest weeds, insects, and pathogens that may require additional pesticides for control.* On some crops like corn, a herbicide like atrazine may persist from one growing season to another and prevent the culture of another crop (e.g., soybeans) that is sensitive to this herbicide. Growing corn continuously year after year may increase some pest weeds, insects, and disease pathogens.

14. *The price support and land retirement programs encouraged intensive agriculture which may include using herbicides as well as other pesticides because increased yields were needed on the restricted acreages.*

15. *In some right-of-way areas, herbicides permit selective vegetation management not otherwise possible.* In extensive areas of rough terrain the aerial application of herbicides provides the only practical method of brush control. Contamination of nontarget areas may occur because rights-of-way are only a few hundred feet wide and extend for many miles through vast wild habitats. Overall, however, the problem of pollution appears to be minor because applications are infrequent and closely regulated.

16. *The control of aquatic plants by herbicides is difficult to manage, and it is even more difficult to assess the ecological impact of control.* The reasons for the difficulties in aquatic systems are (1) natural waters constitute an active transport system for the movement of herbicides out of the target area; (2) lakes, rivers, and estuaries are complex ecological systems, which make understanding the changes caused by herbicides most difficult.

17. *The costs, benefits, and risks to man and his environment in using herbicides are most complex; however, in comparison with insecticides, herbicides are generally a smaller environmental hazard.*

INTRODUCTION

Man's management of his environment for crop production has come into conflict with the preservation of the life system. The effects of this management are not always immediately apparent, and short-term gains tend to be more heavily weighted than long-term losses. Herbicides are an important management tool whose intended effects in plant control represent a significant environmental impact. The purpose of this chapter is not to evaluate the wisdom of the management—the intended effects—but to call attention to the unintended effects that may occur as a result of this particular form of management.

The environmental life system, consisting of an estimated 200,000 species of plants and animals in the United States, is in a vulnerable status. We appear to have reached a crucial stage where the continued increased usage of chemicals for a variety of agricultural and nonagricultural purposes may cause irreversible damage to some essential parts of this life system. Unfortunately, no one knows *how far* the environment may be allowed to deteriorate or *how many* species of plants and animals can be exterminated before man himself is in serious jeopardy.

The immense variety of species in the life system results from the inherent design in both the structure and the function of plants and animals. Each has been specifically structured through evolution to function in a certain way in its particular environment. Thus some species are cold hardy, some tolerate dry conditions, some require an alkaline-sandy soil, some need light, some need vitamin B_{12}, and so forth. From the bacterium to the moose, some of the survival requirements for each kind of animal and plant are unique.

Man depends on a great variety of species for the maintenance of a quality atmosphere, for an adequate food supply, and for the biological degradation of wastes. In the presence of sunlight, plants take in carbon dioxide and water, and release oxygen, which is needed by man and other animals. The oxygen also yields ozone, which screens out lethal solar ultraviolet rays from the earth's surface. In addition, the plants are food for many animals, passing their life-making elements (carbon, oxygen, hydrogen, nitrogen, and others) to the animals in the food chain. Eventually, microorganisms feeding on wastes and dead animals and plants release vital elements for reuse by the plants. In this way countless species of the life system interact and function to keep the life-making elements recycling in the environment. Thus man depends on the other species of the life system, and, indeed, plants, man, and other animals are all functioning parts of the same "establishment."

Now, when quantities of pollutants are increasing, species populations of the life system serve another valuable role: as "indicators" of when pollutant dosages are reaching dangerous levels in the environment. If we acknowledge the contribution all species make in keeping the life system functioning and in indicating danger, we must recognize that man's welfare is threatened when chemical pollutants, including herbicides, affect other species of the environmental life system. In general, chemical pollutants as well as nonchemical manipulations, such as the construction of roads and channels, may have a disruptive and deleterious impact on life systems (PSAC, 1965). The impact of chemical pollutants on life systems includes the following:

1. The number of species constituting a life system is often reduced after exposure to chemical pollutants.

2. Significant reductions in the number of species may lead to instability within a life system and subsequently to population outbreaks of some species because the normal check-balance

structure of the system is altered. For example, when a species of predator, parasite, or competitor that limits the increase of another species is reduced, the population once held in check may increase explosively.

3. After the disappearance of a pollutant from the affected area, populations eventually regain their balance. For a time, however, those species populations low in the food chain (e.g., the herbivorous animals or plant feeders) are usually the ones to increase to outbreak levels. This often results in a serious disruption of the ecosystem in the affected area.

4. Predator and parasite species high in the food chain are quite susceptible both to the loss of a species and to extreme population fluctuations of species low in the food chain on which they depend. Thus, when a species low in the food chain is affected, the many dependent species also suffer, and the check-balance mechanism is made more uncertain.

In the United States during 1971 about 353 million pounds of herbicides were aimed at several hundred weed species (USDA, 1973). In the process the populations of many nontarget plant and animal species in the environmental life system were directly or indirectly affected by the herbicides.

This chapter briefly evaluates the available evidence concerning the environmental impact of herbicide use. Particular attention is focused on residues in air, water, soil, and organisms, as well as environmental effects related to crop, aquatic, industrial, and conservation uses. Emphasis is placed not only on the identification of ecological consequences but also on possible alternatives and less hazardous usage of herbicides.

SOURCES AND MOVEMENT OF HERBICIDES IN THE ENVIRONMENT

The environmental contamination of target and nontarget areas depends on (1) toxicity of herbicide, (2) biomagnification, (3) persistence, (4) amount used, (5) application method, and (6) movement. Although the toxicity of herbicides to animals varies widely, herbicides as a class are less toxic than insecticides. Biomagnification occurs primarily in plants, which can be a hazard, but seldom in animals. Persistence increases the chances of a herbicide's becoming a pollutant. This is because the longer a material remains in the environment, the greater the opportunity for the chemical to be a problem within the target area or to move out of the treated area and become a hazard elsewhere.

In terms of the amount used, the pollution problem is clear and needs no explanation. Application methods determine the amount of herbicide used and the extent of environmental contamination. Of major concern is the extensive use of aerial application: 15 to 20 percent of all agricultural herbicides is applied by aircraft (USDA, 1972). Akesson and Yates (1971) report that spray recoveries from aircraft applications may be as low as 25 to 30 percent of the amount applied. Widespread drift effects from aircraft applications have occurred, for example, in California. Propanil was applied to rice and injury to fruit trees was observed about 55 miles downwind (Akesson, 1971).

Airborne concentrations harmful to nontarget crops are most frequently due to drift at the time of application of the herbicide to the target. Usually residues on plants contaminated from drift are far lower than those on the target species of plants; however, sensitive plants, such as cotton and grapes, are particularly vulnerable to 2,4-D and, under rare weather circumstances, may be damaged by residues as much as 15 miles from the point of application. However, damage most frequently occurs within 500 feet (Van Middelem, 1966).

Herbicide residues due to drift are most closely correlated with the type of equipment used, herbicide formulation, and wind velocity. Most serious drift problems can be solved by modifying equipment; using such formulations as granules, inverted emulsions, and spray thickeners; and avoiding small particulates and windy days for application (Butler *et al.*, 1969; Akesson *et al.*, 1971; Akesson *et al.*, 1972). Particles of soil, spray droplets, and rain droplets that can be carried by normal wind velocities of 5 mph for over 100 feet vary from less than 5 to 100 microns in diameter (Reimer *et al.*, 1966). Assuming particles to have nearly equal deposition of the herbicide on treated soil, particles 10 microns in diameter will have a surface area 1000 times as great per volume as particles 100 microns in diameter and consequently about 100 times the residue in parts per million, assuming no volatility.

The operational techniques utilized to apply the spray and the microclimate at the time of application are also important variables that affect drift. Climatic inversion conditions, not infrequent in parts of the United States, can result in a particularly acute drift problem because the movement of the spray (especially small particles) is concentrated near ground level in a horizontal direction--often far from the target area. Applying herbicides with winds of 10 mph or greater generally causes the most problems with herbicide drift.

Herbicides move from treated land areas primarily via vaporization and also by rain and irrigation water. For example, both 2,4-D esters and EPTC vaporize rapidly and may affect nontarget plants in the near vicinity. The use of 2,4-D near certain crops has been restricted in some states (e.g., California and Texas) to prevent damage to highly sensitive crops. Most of the herbicides mentioned in Table 1 are more soluble in water than are insecticides. Although soluble and susceptible to leaching, the amounts found in water outside the target area are small (White *et al.*, 1967; Axe *et al.*, 1969). The relative mobility of pesticides in soil leaching experiments show phenoxy and picloram herbicides to be most mobile, followed by a group of miscellaneous herbicides, then by phenylureas, triazines, and other related herbicides, and then by CIPC and toluidine herbicides (Norris and Moore, 1970). Herbicides, however, in runoff soil and water from certain treated areas such as crops and roadsides may result in some pollution problems.

Various agents are added to certain herbicide formulations to increase their efficiency of contact with the plant surface and their duration of contact. These additives include oil emulsifiers as well as thickeners (cellulose, alginates, swellable polymers) and foam additives. These additives may also result in coarser sprays and hence a reduction of drift. Viscosity additives have been used particularly for industrial applications. Thus any consideration of the environmental impact of herbicides must also consider the action and fate of additives (as well as impurities, as occurred with 2,4,5-T). For example, although certain additives may result in a drift reduction, they can also retard herbicide degradation rates (Akesson and Yates, 1971). Furthermore, such carriers as diesel oil, which is used commonly in forestry practices, may constitute 80 to 90 percent of the spray solution (Tarrant and Norris, 1967).

Once a herbicide has been directed at a target system, what happens to it? As stated earlier, depending on application procedures, a portion of the herbicide may never hit the target, but rather disperse by drift. That which does hit the target may be lost from it through a variety of routes, including runoff, erosion, leaching, and volatilization, or perhaps even through migration of the biota (Figure 1).

Within the target system, the breakdown of herbicides is generally fairly rapid, either within the soil system or in the above-ground food chain. The herbicide is largely deactivated in the plant, although it can be lost from the plant by a variety of routes, including exudation by roots into the rhizosphere (Reid and Hurtt, 1970), where it may be broken down. There does not appear to be bioconcentration of herbicides in higher trophic levels. The flesh of deer that had eaten vegetation treated with 2,4,5-T or atrazine rarely had detectable residues (Newton and Norris, 1968). Even in soils of rangeland treated with the relatively persistent picloram, this agent usually totally dissipates within a year (Scifres *et al.*, 1971).

Table 1. TOXICITY OF HERBICIDES TO MAMMALS, BIRDS, FISH, AND INVERTEBRATES

Common name (trade name) of herbicide	Name of organism	Type of test exposure	Dosage	Effect	Reference
Acrolein (Aqualin, Hydrothal)	Rat	Acute oral	46 mg/kg	LD_{50}	Anon. (1970)
	Rabbit	Acute oral	7 mg/kg	LD_{50}	
	Rat	Water dietary, 90-day	200 ppm	No effect	
	Bluegill	Acute, 96-hr	0.1 ppm	LC_{50}	Lawrence (1963)
	Chinook salmon	Acute, 24-hr	0.08 ppm	LC_{50}	
	Coho salmon	Acute, 0.25-hr	2.0 ppm	100% mortality	
	Rainbow trout	Acute, 24-hr	0.14 ppm	LC_{50}	Pimentel (1971)
	Largemouth bass	Acute, 96-hr	0.16 ppm	LC_{50}	Lawrence (1963)
	Mosquito fish	Acute, 48-hr	0.06 ppm	LC_{50}	
	Fathead minnow	Acute, 48-hr	0.015 ppm	LC_{50}	
	Bluegill	Acute,[1] 24-hr	0.079 ppm	LC_{50}	Battelle (1971)
	Brown trout	Acute,[1] 24-hr	0.046 ppm	LC_{50}	
Alachlor (Lasso)	Rat	Acute oral	774 mg/kg[2]	LD_{50}	Anon. (1970)
		Dietary, 90-day	200 ppm	No effect	
	Pheasant	Dietary, 5-day?	>4300 ppm	LC_{50}	
	Rainbow trout	Acute, 96-hr	1.0 ppm[3]	LC_{50}	
	Bluegill	Acute, 96-hr	5.8 ppm[3]	LC_{50}	
Atrazine	Rat	Acute oral	3080 mg/kg	LD_{50}	Anon. (1970)
	Mouse	Acute oral	1750 mg/kg	LD_{50}	
	Rat	Dietary, 2-yr	100 ppm	No effect	
	Cattle	Acute oral	50 mg/kg	Significant effect[5]	Palmer and Radeleff (1969)
		2 CDOD[4]	25 mg/kg	Significant effect[5]	
		10 CDOD[4]	10 mg/kg	No effect	
	Sheep	Acute oral	100 mg/kg	Significant effect[5]	
		3 CDOD[4]	50 mg/kg	Significant effect[5]	
		8 CDOD[4]	25 mg/kg	Significant effect[5]	
	Bobwhite	Dietary, 5-day	>5000 ppm	LC_{50}	Heath *et al.* (1972)
	Mallard	Dietary, 5-day	>5000 ppm	LC_{50}	
	Japanese quail	Dietary, 5-day	>5000 ppm	LC_{50}	
	Ring-necked pheasant	Dietary, 5-day	>5000 ppm	LC_{50}	
	Chicken	10 CDOD[4]	50 mg/kg	Significant effect[5]	Palmer and Radeleff (1969)
		10 CDOD[4]	25 mg/kg	No effect	
	Spot	Acute, 48-hr	1 ppm	No mortality	Pimentel (1971)
	Harlequin fish	Acute, 24-hr	0.55 ppm	LC_{50}	
	Rainbow trout	Acute, 96-hr	4.5 ppm	LC_{50}	EPA (1972)
	Bluegill	Acute, 48-hr	26 ppm	LC_{50}	
	E. Oyster	Acute, 96-hr, flowing seawater	1 ppm	No effect	Pimentel (1971)
	Brown shrimp	Acute, 48-hr	1 ppm	30% mortality or loss of equilibrium	
	Water flea (*Daphnia magna*)	Acute, 48-hr	3.6 ppm	LC_{50}	Pimentel (1971)
Butylate (Sutan)	Rat	Acute oral	4659-5431 mg/kg	LD_{50}	Anon. (1970)
	Guinea pig	Acute oral	1659 mg/kg	LD_{50}	
	Rat	Dietary, 90-day	32 mg/kg-day	No effect	
	Dog	Dietary, 90-day	40 mg/kg-day	No effect	
	Bobwhite	Dietary, 7-day	40,000 ppm	LC_{50}	
	Bluegill	Acute, 96-hr	6.9 ppm	LC_{50}	
	Rainbow trout	Acute, 96-hr	4.2 ppm	LC_{50}	
	Gammarus fasciatus	Acute, 96-hr	10.0 ppm	LC_{50}	Sanders (1970a)

Table 1. TOXICITY OF HERBICIDES TO MAMMALS, BIRDS, FISH, AND INVERTEBRATES–Continued

Common name (trade name) of herbicide	Name of organism	Type of test exposure	Dosage	Effect	Reference
Chloramben (Amiben)	Rat	Acute oral	5620 mg/kg	LD$_{50}$	Anon. (1970)
		Dietary, 2-yr	10,000 ppm	No effect	
	Cattle	10 CDOD[4]	250 mg/kg	Significant effect[3]	Palmer (1972)
		10 CDOD[4]	175 mg/kg	No effect	
	Sheep	2 CDOD[4]	50 mg/kg	Significant effect[3]	
		10 CDOD[4]	25 mg/kg	No effect	
	Bobwhite	Acute oral	>700 mg/kg	LD$_{50}$	EPA (1972)
	Chicken	7 CDOD[4]	500 mg/kg	Significant effect[3]	Palmer (1972)
		10 CDOD[4]	375 mg/kg	Significant effect[3]	
		10 CDOD[4]	250 mg/kg	No effect	
	Rainbow trout	Acute, 96-hr	4.2 ppm	LC$_{50}$	EPA (1972)
	Bluegill	Acute, 96-hr	1000 ppm	LC$_{50}$	
Copper sulfate[5]	Sheep	Dietary	25 mg/day	Jaundice	Pimentel (1971)
	Mallard	Acute oral	>2000 mg/kg[6]	LD$_{50}$	
	Ring-necked pheasant	Acute oral	>2000 mg/kg[6]	LD$_{50}$	
	Bluegill	Acute, 24-hr	1.5 ppm	LC$_{50}$	
	Striped bass	Acute, 48-hr	0.15 ppm	LC$_{50}$	
	Bluegill	Acute, 96-hr	3.0 ppm	Tolerated	Lawrence (1962)
	Bass	Acute, 96-hr	3.0 ppm	Tolerated	
	Goldfish	Acute, 96-hr	1.0 ppm	Tolerated	
	Fathead minnow	Acute, 96-hr	1.0 ppm	Tolerated	
	Daphnia	Acute, 16-hr	0.1 ppm	EC$_{50}$[7]	
	Daphnia	Acute, 2-hr	100 ppm	100% mortality	
2,4-D (acid)[8]	Rat	Acute oral	666 mg/kg	LD$_{50}$	Pimentel (1971)
	Mouse	Acute oral	375 mg/kg	LD$_{50}$	
	Rabbit	Acute oral	800 mg/kg	LD$_{50}$	
	Dog	Acute oral	100 mg/kg	LD$_{50}$	
	Guinea pig	Acute oral	1000 mg/kg	LD$_{50}$	
	Mule deer	Acute oral	400-800 mg/kg	LD$_{50}$	
	Rat	Dietary, 2-yr	1250 ppm	No effect	Hansen *et al.* (1971)
	Dog	Dietary, 2-yr	500 ppm	No effect	
	Rat	Three-generation reproduction	500 ppm	No effect	
	Cattle	Acute oral	250 mg/kg[9]	Significant effect[3]	Palmer (1972)
		25 CDOD[4]	200 mg/kg[9]	Significant effect[3]	
		86 CDOD[4]	100 mg/kg[9]	Significant effect[3]	
		112 CDOD[4]	50 mg/kg[9]	No effect	
	Sheep	7 CDOD[4]	500 mg/kg[9]	Significant effect[3]	
		10 CDOD[4]	250 mg/kg[9]	Significant effect[3]	
		8 CDOD[4]	100 mg/kg[9]	No effect	
	Mallard	Acute oral	>1000 mg/kg	LD$_{50}$	Pimentel (1971)
		Dietary, 5-day	>5000 ppm[8]	LC$_{50}$	
	Ring-necked pheasant	Acute oral	472 mg/kg	LD$_{50}$	
		Dietary, 5-day	>5000 ppm[8]	LC$_{50}$	
	Japanese quail	Acute oral	668 mg/kg	LD$_{50}$	
		Dietary, 5-day	>5000 ppm[8]	LC$_{50}$	
	Pigeon	Acute oral	668 mg/kg	LD$_{50}$	
	Chicken	10 CDOD[4]	500 mg/kg[9]	Significant effect[3]	Palmer (1972)
		10 CDOD[4]	250 mg/kg[9]	Significant effect[3]	
		10 CDOD[4]	100 mg/kg[9]	No effect	
	Chorus frog tadpole	Acute, 24-hr	100 ppm	LC$_{50}$	Pimentel (1971)
	Bluegill	Acute, 24-hr	5 ppm	No mortality	Applegate *et al.* (1957)
	Rainbow trout	Acute, 24-hr	5 ppm	No mortality	
	Daphnia magna	Acute, 48-hr	>100 ppm	LC$_{50}$	Sanders (1970a)
	Gammarus fasciatus	Acute, 48-hr	3.2 ppm	LC$_{50}$	

Table 1. TOXICITY OF HERBICIDES TO MAMMALS, BIRDS, FISH, AND INVERTEBRATES—Continued

Common name (trade name) of herbicide	Name of organism	Type of test exposure	Dosage	Effect	Reference
Diuron (Karmex)	Rat	Acute oral	3400 mg/kg	LD_{50}	Anon. (1970)
	Rat (Low Chronic Toxicity)				
	Cattle	10 CDOD[4]	100 mg/kg	Significant effect[3]	Palmer and Radeleff (1969)
		10 CDOD[4]	50 mg/kg	No effect	
	Sheep	Acute oral	250 mg/kg	Significant effect[3]	
		2 CDOD[4]	100 mg/kg	Significant effect[3]	
		10 CDOD[4]	50 mg/kg	No effect	
	Bobwhite	Dietary, 5-day	1730 ppm	LC_{50}	Heath *et al.* (1972)
	Japanese quail	Dietary, 5-day	>5000 ppm	LC_{50}	
	Ring-necked pheasant	Dietary, 5-day	>5000 ppm	LC_{50}	
	Mallard	Dietary, 5-day	>5000 ppm	LC_{50}	
	Chicken	10 CDOD[4]	10 mg/kg	Significant effect[3]	Palmer and Radeleff (1969)
		10 CDOD[4]	5 mg/kg	No effect	
	Bullfrog tadpole	Acute	10 ppm	100% mortality	Lawrence (1963)
	Rainbow trout	Acute, 48-hr	4.3 ppm	LC_{50}	Pimentel (1971)
	Coho salmon	Acute, 48-hr	42 ppm	LC_{50}	
	Largemouth bass	Acute, 48-hr	16 ppm	LC_{50}	
	Bluegill	Acute, 24-hr	9.7-27 ppm[10]	LC_{50}	
	White crappie	Acute, 24-hr	8.75 ppm	50% mortality	
	Striped bass	Acute, 96-hr	3.1 ppm	LC_{50}	
	Daphnia pulex	Acute, 48-hr	1.4 ppm	LC_{50}	
	Gammarus	Acute, 48-hr	0.38 ppm	LC_{50}	
	E. Oyster	Acute, 96-hr, flowing saltwater	1.8 ppm	Shell growth decreased	Battelle (1971)
	Brown shrimp	Acute, 48-hr, flowing saltwater	1.0 ppm	No effect	
Endothall	Rat	Acute oral	38-51 mg/kg	LD_{50}	Anon. (1970)
		Dietary, 2-yr	>300 ppm[11]	No effect	
	Dog	Dietary, 2-yr	>300 ppm[11]	No effect	
	Cattle	2 CDOD[4]	25 mg/kg[12]	Significant effect[3]	Palmer (1972)
		10 CDOD[4]	10 mg/kg[12]	No effect	
	Sheep	2 CDOD[4]	50 mg/kg[12]	Significant effect[3]	
		2 CDOD[4]	25 mg/kg[12]	Significant effect[3]	
		10 CDOD[4]	10 mg/kg[12]	Significant effect[3]	
		10 CDOD[4]	5 mg/kg[12]	No effect	
	Chicken	10 CDOD[4]	10 mg/kg[12]	Significant effect[3]	
	Bluegill	Acute, 96-hr	125 ppm[13]	LC_{50}	Pimentel (1971)
	Carp	Acute, 96-hr	175 ppm[13]	LC_{50}	
	Largemouth bass	Acute, 96-hr	120-200 ppm[13]	LC_{50}	
	Fathead minnow	Acute, 96-hr	320-610 ppm[13]	LC_{50}	Lawrence (1963)
	Daphnia magna	Acute, 24-hr?	46 ppm	EC_{50}[14]	Pimentel (1971)
	Gammarus lacustris	Acute, 24-hr	2 ppm	LC_{50}	Sanders (1970a)
Linuron (Lorox)	Rat	Acute oral	1500 mg/kg	LD_{50}	Martin (1968)
		Acute oral	4000 mg/kg	LD_{50}	
	Dog	Acute oral	500 mg/kg	LD_{50}	
	Cattle	6 CDOD[4]	100 mg/kg	Significant effect[3]	Palmer and Radeleff (1969)
		10 CDOD[4]	50 mg/kg	Significant effect[3]	
		10 CDOD[4]	25 mg/kg	No effect	
	Sheep	4 CDOD[4]	100 mg/kg	Significant effect[3]	
		1 CDOD[4]	50 mg/kg	Significant effect[3]	
		10 CDOD[4]	25 mg/kg	No effect	
	Chicken	10 CDOD[4]	10 mg/kg	Significant effect[3]	
	Carp	Acute, 48-hr	>10 ppm	LC_{50}	EPA (1972)

Table 1. TOXICITY OF HERBICIDES TO MAMMALS, BIRDS, FISH, AND INVERTEBRATES–Continued

Common name (trade name) of herbicide	Name of organism	Type of test exposure	Dosage	Effect	Reference
Nitralin (Planavin)	Rat	Acute oral	>2000 mg/kg	LD_{50}	Anon. (1970)
	Mouse	Acute oral	>2000 mg/kg	LD_{50}	
	Rat	Dietary, 2-yr	2000 ppm	No effect?	
	Cattle	2 CDOD^{4}	250 mg/kg	Significant effect^{3}	Palmer (1972)
		10 CDOD^{4}	175 mg/kg	No effect	
	Sheep	4 CDOD^{4}	500 mg/kg	Significant effect^{3}	
		10 CDOD^{4}	250 mg/kg	No effect	
	Chicken	Acute oral	>1000 mg/kg	LD_{50}	Martin (1968)
		10 CDOD^{4}	500 mg/kg	No effect	Palmer (1972)
	Bluegill	Acute, 48-hr	20 ppm	No mortality	Martin (1968)
	? Trout	Acute, 48-hr	20 ppm	No mortality	
	Goldfish	Acute, 48-hr	20 ppm	No mortality	
	Silver salmon	Acute, 48-hr	20 ppm	No mortality	
Propachlor (Ramrod)	Rat	Acute oral	710 mg/kg	LD_{50}	Anon. (1970)
		Dietary, 90-day	133 mg/kg-day	No effect	
	Cattle	3 CDOD^{4}	25 mg/kg	Significant effect^{3}	Palmer (1972)
		10 CDOD^{4}	10 mg/kg	No effect	
	Sheep	4 CDOD^{4}	50 mg/kg	Significant effect^{3}	
		9 CDOD^{4}	10 mg/kg	Significant effect^{3}	
		10 CDOD^{4}	5 mg/kg	No effect	
	Ring-necked pheasant	Acute oral	735 mg/kg	LD_{50}	Anon. (1970)
	Chicken	3 CDOD^{4}	1000 mg/kg	Significant effect^{3}	Palmer (1972)
		10 CDOD^{4}	10 mg/kg	Significant effect^{3}	
		10 CDOD^{4}	5 mg/kg	No effect	
	Bluegill	Acute, 96-hr	1.3 ppm	LC_{50}	Anon. (1970)
	Fathead minnow	Acute, 96-hr	0.49 ppm	LC_{50}	
Propazine (Milogard)	Rat	Acute oral	>5000 mg/kg	LD_{50}	Anon. (1970)
	Mouse	Acute oral	>5000 mg/kg	LD_{50}	
	Rat	130 CDOD^{4}	250 mg/kg	No effect	
	Cattle	2 CDOD^{4}	250 mg/kg	Significant effect^{3}	Palmer and Radeleff (1969)
		3 CDOD^{4}	25 mg/kg	Significant effect^{3}	
		10 CDOD^{4}	10 mg/kg	No effect	
	Sheep	Acute oral	500 mg/kg	Significant effect^{3}	
		10 CDOD^{4}	100 mg/kg	Significant effect^{3}	
		5 CDOD^{4}	25 mg/kg	Significant effect^{3}	
		10 CDOD^{4}	10 mg/kg	No effect	
	Bobwhite	(Low toxicity)			Anon. (1970)
	Mallard	(Low toxicity)			
	Chicken	6 CDOD^{4}	250 mg/kg	Significant effect^{3}	Palmer and Radeleff (1969)
		10 CDOD^{4}	100 mg/kg	Significant effect^{3}	
		25 CDOD^{4}	25 mg/kg	No effect	
	Rainbow trout	Acute, 96-hr	>100 ppm	LC_{50}	EPA (1972)
		Acute, 48-hr	7.8 ppm	LC_{50}	Pimentel (1971)
	Goldfish	Acute, 48-hr	>32 ppm	LC_{50}	EPA (1972)
	Bluegill	Acute, 48-hr	>100 ppm	LC_{50}	
Trifluralin (Treflan)	Rat	Acute oral	>10,000 mg/kg	LD_{50}	Pimentel (1971)
	Mouse	Acute oral	5000 mg/kg	LD_{50}	
	Dog	Acute oral	>2000 mg/kg	LD_{50}	
	Rabbit	Acute oral	>2000 mg/kg	LD_{50}	
	Rat	Dietary, 2-yr	>2000 ppm/day	No effect	Anon. (1970)
	Dog	Daily, 2-yr dietary capsule	>1000 ppm	No effect	
	Cattle	2 CDOD^{4}	175 mg/kg	Significant effect^{3}	Palmer and Radeleff (1969)
		10 CDOD^{4}	100 mg/kg	No effect	

Table 1. TOXICITY OF HERBICIDES TO MAMMALS, BIRDS, FISH, AND INVERTEBRATES—Continued

Common name (trade name) of herbicide	Name of organism	Type of test exposure	Dosage	Effect	Reference
Trifluralin (Treflan) (continued)	Sheep	2 CDOD[4]	175 mg/kg	Significant effect[3]	
		10 CDOD[4]	100 mg/kg	No effect	
	Ring-necked pheasant	Acute oral	>2000 mg/kg	LD_{50}	Pimentel (1971)
	Chicken	Acute oral	>2000 mg/kg	LD_{50}	
	Mallards	Acute oral	>2000 mg/kg	LD_{50}	
	Chicken	10 CDOD[4]	500 mg/kg	Significant effect[3]	Palmer and Radeleff (1969)
		10 CDOD[4]	250 mg/kg	Significant effect[3]	
		10 CDOD[4]	100 mg/kg	No effect	
	Rainbow trout	Acute, 96-hr	0.01-0.086 ppm	LC_{50}	EPA (1972)
	Fathead minnow	Acute, 96-hr	0.093 ppm	LC_{50}	Battelle (1971)
	Bluegill	Acute, 96-hr	0.019-0.089 ppm	LC_{50}	EPA (1972)
	Channel catfish	Acute, 96-hr	0.254 ppm	LC_{50}	
	Goldfish	Acute, 96-hr	0.252 ppm	LC_{50}	
	Daphnia magna	Acute, 48-hr	0.56 ppm	LC_{50}	Sanders (1970a)
	Daphnia pulex	Acute, 48-hr	0.24 ppm	LC_{50}	Pimentel (1971)
	Gammarus lacustris	Acute, 48-hr	5.6 ppm	LC_{50}	
	Gammarus fasciatus	Acute, 48-hr	1.0 ppm	LC_{50}	Sanders (1970a)
	Crayfish *(Orconectes nais)*	Acute, 48-hr	50.0 ppm	LC_{50}	
Xylene	Rat	Acute oral	4300 mg/kg	LD_{50}[15]	McKee and Wolf (1971)
	Various species of fish	Acute	10-90 ppm	Will kill fish[16]	
	Bluegill	Acute, 24-hr	5 ppm	Sick	
	Rainbow trout	Acute, 24-hr	5 ppm	No mortality	
	Sea lamprey	Acute, 24-hr	5 ppm	No mortality	
	Orange-spotted sunfish	Acute, 1-hr	47 ppm	Kill	Lawrence (1962)
	Daphnia magna	Acute, 48-hr	0.01-0.1 ppm	Kill	

[1] Continuous flow.

[2] Corrected for 4-lb/gal emulsifiable composition, probably 43 percent a.i.

[3] Weight loss, reduced weight gain, or illness.

[4] CDOD = consecutive daily oral doses each at the given dosage.

[5] Toxicity varies greatly with pH and turbidity.

[6] Bordeaux mixture.

[7] Dead or immobilized.

[8] There is very little variation in toxicity among the various salts and esters of 2,4-D in mammals and birds; however, certain esters are much more toxic than the acid to fish (∿1 ppm).

[9] Alkanolamine salts.

[10] Different temperatures.

[11] Disodium salt.

[12] Potassium salt.

[13] Cocoamine, dimethylamine, and copper salts may be toxic to fish at less than 1 ppm.

[14] Immobilization.

[15] Usually a mixture of *o*-, *m*-, and *p*-xylene.

[16] *m*-Xylene—usually the most toxic of the isomers.

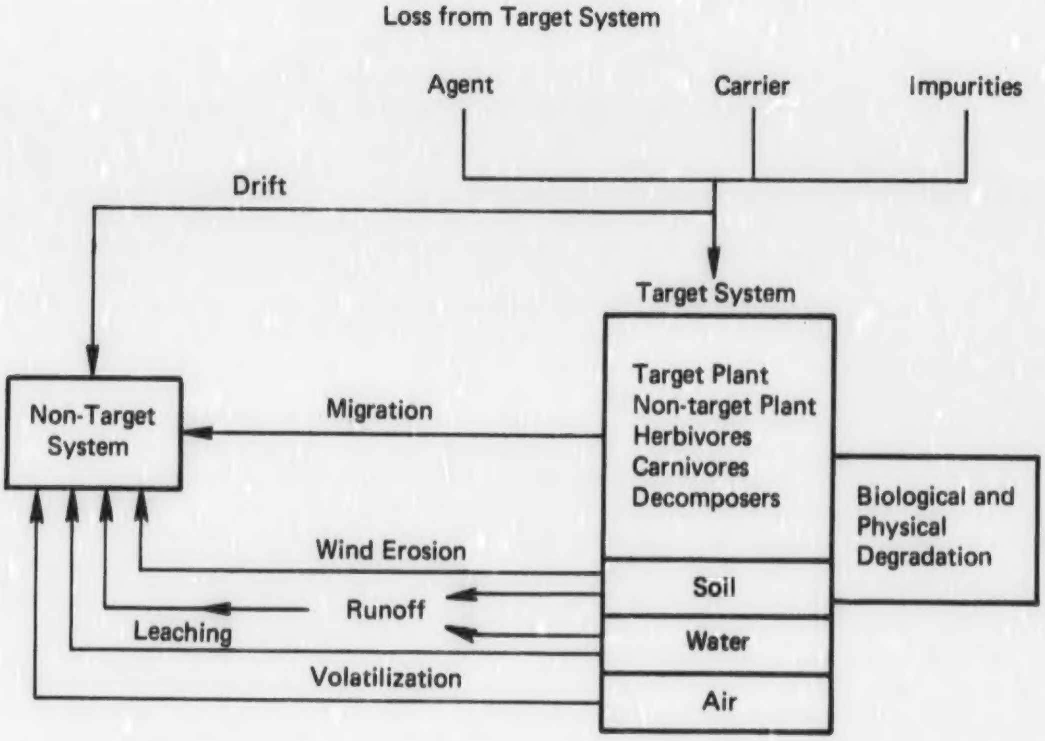
Loss from Target System
Agent
Carrier
Impurities
Drift
Target System
Target Plant
Non-target Plant
Herbivores
Carnivores
Decomposers
Non-Target System
Migration
Biological and Physical Degradation
Wind Erosion
Soil
Runoff
Leaching
Water
Volatilization
Air

Figure 1. Potential pathways for the loss of herbicides from target systems

RESIDUES OF HERBICIDES

The herbicide-residue level in the environment is related to the dosage applied, the number of applications, the method of application, the type of herbicide formulation, habitat, wind, sunlight, oxygen, rain, the soil type (especially to organic matter, clay minerals, pH, temperature), microorganisms (aerobic or anaerobic), the time after application, and so forth. Relative levels of these residues can be predicted with reasonable accuracy from a correlation of the physical, chemical, and biological properties of the different kinds of herbicides with the above environmental variables and with herbicide uses and application methods (Freed, 1966; Van Middelem, 1966; Kenaga, 1968).

The determination of herbicide residues must include the products of molecular transformations such as hydrolysis, oxidation, and reduction. Also, consideration must be given to the ingredients of the formulation and the impurities present, whether due to manufacture, packaging, or storage of the material. One need only study the development of such pesticides as 2,4,5-T (and its toxic tetrachlorodibenzo-*p*-dioxin trace impurity) to realize the importance of the above determinations. In fact, few herbicides have been subjected to detailed analysis for product impurities at the 1-ppm level.

Reactions associated with the microbial metabolism of herbicides include *N*-dealkylation of ureas, ester or amide hydrolysis of carbamates, side-chain degradation of the *s*-triazines, and dechlorination of 2,4-D and dalapon (Kearney, 1966). Not all herbicides are metabolized directly to smaller molecules. For example, propanil converted microbially to 3,4-dichloroaniline is thought to form a larger molecule by diazotization by the nitrate ion in the soil (Rosen, 1972).

Bioaccumulation of Residues

The use of the terms "bioaccumulation" and "bioconcentration" often conjures up the image of the type of residue accumulation that occurs with DDT in animal organisms, especially in their fat tissues. The bioconcentration factor (biomagnification) is the ratio of the measured residue in an animal or plant (or a specific tissue) to the measured residue in the ambient air, water, or soil environment of the organism and/or the various species of food organisms consumed, as specified (Kenaga, 1972). The highest bioconcentration factors with insecticides usually occur in water. DDT and its degradate DDE may have a bioconcentration factor of a million. Such herbicides as picloram (Hardy, 1966), Silvex (Getzendaner, 1960), 2,4-D (Cope *et al.*, 1970; Smith and Isom, 1967), and dichlobenil (Cope *et al.*, 1969) do not appear to bioconcentrate in fish or aquatic organisms more than tenfold and often not at all. Diuron may have a bioconcentration factor of several hundred (McCraren *et al.*, 1969).

Although oysters and clams may accumulate from 3.6 to 3.8 ppm of 2,4-D in herbicidally treated areas such as Chesapeake Bay, they cleanse themselves of residues before harvest time (Frank, 1971). Butler (1965) exposed oysters continuously for 7 days to 0.1 ppm of 2,4-D butoxyethanol ester. The oysters accumulated 18 ppm and cleansed themselves in 7 days with fresh seawater. Fish in treated ponds may retain the residues of some herbicides for weeks (McCraren *et al.*, 1969; Cope *et al.*, 1969).

The important fact concerning chronic toxicity is not how large the bioconcentration factor is, but how much actual residue (in parts per million) bioaccumulates.

The terms "bioaccumulation" and "bioconcentration" may be applied to plants, but generally speaking, the properties of a chemical used to penetrate and kill insects are quite different from those needed to penetrate and kill plants. Among other things, insecticides that are nonsystemic poisons are often quite high in fat solubility (in order to penetrate insects) and low in water solubility. Thus stable compounds may be bioaccumulated in animal fats and be consumed by other animals. Most herbicides tend to have greater water solubility and/or do not partition as greatly in favor of fat tissues as do DDT and other organochlorine insecticides. Further degradation of most herbicides leads to products that are even more water soluble—for example, atrazine to hydroxyatrazine and prometryne to hydroxypropazine (Shimabukuro and Swanson, 1969; Frans *et al.*, 1972). Many herbicides penetrate plants and are redistributed, especially in the growing portions of the plants, such as leaves and roots. Because herbicide residues on treated plant foliage are often determined for the whole leaf, the differences between surface and internal residue concentration are often not appreciated.

Assuming an even coverage of herbicide on the surface of various plants, the residues vary greatly in parts-per-million values since the surface-to-volume ratios of the different parts of plants and different species of plants do vary. In a literature study of many pesticides, the maximum residues of pesticides were calculated on a 1-lb/acre basis by dividing the residues determined by analysis by the dosage in pounds per acre applied (Hoerger and Kenaga, 1972). Such *maximum* residues, immediately after application, ranged from 6.6 ppm for fruits to 240 ppm for foliage such as grass, depending on the surface-to-volume ratio (size and shape of vegetation sprayed). The highest amounts of residues occurred with systemic herbicides and insecticides on foliage. Most residues were far lower than the maximum residues cited above. All residues declined within days after application, although some traces persisted for months at levels above the limit of analytical sensitivity (Hoerger and Kenaga, 1972).

Duggan *et al.* (1971) reported on pesticide levels in foods and feeds in the United States from 1963 to 1969. The only herbicides found were 2,4-D, MCP, and dacthal. None was found commonly or in amounts exceeding parts per billion.

Residues in Soil

A major problem in assaying herbicide residues in soil is the accurate measurement of actual amounts of the compound and/or its degradation products at varying time periods after application. Only a few studies include a wide variety of the most commonly used herbicides tested comparatively in the field (Table 2). A Southern State Regional Cooperative Study (Frans *et al.*, 1972) showed that no phytotoxic residues of atrazine, chlorpropham, DCPA, diphenamid, diuron, linuron, norea, prometryne, or trifluralin persist in soil after 1 year when applied at recommended rates; however, no analytical residue data accompanied this phytotoxicity data. Herbicide residues are likely to persist two or more times longer in the colder areas of the United States and Canada. In Oregon, studies of chemical brush control with 2,4-D, amitrole, 2,4,5-T, and picloram indicated that detectable residues of picloram persisted for more than a year while the rest degraded more rapidly (Norris, 1971).

Analytical work shows that, even though phytotoxicity may not occur on the target crop in soil treated year after year, residues of the herbicide (and degradates) may still be bound to the soil and may be subject to release under certain circumstances. The nature and mechanism of the binding and releasing of pesticide residues held by lignin, humus, cellulose, and other organic matter is uncertain, and residues may sometimes be a problem in the rotation of crops sensitive to herbicides.

All compounds leach to some degree. Anderson *et al.* (1969) discussed the various factors related to leachability, relating it to soil pH as well as mineral and organic content. Two closely related compounds, trifluralin and nitralin, vary greatly in leachability. Even mineral soils are capable of strong adsorption, for example, of phenolic and phenoxyacetic acid herbicides. The adsorption of such compounds is near a maximum when the calculated ionization is about 15 to 30 percent and when the pH approaches the pK_a of the herbicide in water (Miller, 1972).

Table 2. PERSISTENCE OF HERBICIDES IN SOIL IN FIELD TESTS[1]

Herbicide	Amount applied to soil (lb/acre)	Residual phytotoxicity (months)
Alachlor	1-4	1.5-2.5
Atrazine	2-4	4-7[2]
	2-3	4-7[2]
	3-8	12[2]
	2-4	< 12 - > 12
Butylate	3-4	0.12-0.75[3]
Chloramben	2-4	1.5-2
2,4-D	3-4	0.25-1
Diuron[2]	3.6-4	5-7[2]
	1-2	4-8[2]
	2	15[2]
	0.6-6.4	One growing season
Endothall	12	1[2]
Linuron	4	< 4[2]
	0.5-3	4
Nitralin	0.5-1.5	"Moderately persistent"
Propachlor	3-6	1-1.5
Propazine	1-4	< 12
	3	2[2]
	1.8	14[2]
Trifluralin	4	5[2]
	0.5-1	4-6

[1] Unless otherwise indicated, data are from the *Herbicide Handbook of the Weed Society of America* (Anon., 1970). Average residual phytotoxic life given for stated dosages, which are the recommended crop-use dosages.

[2] Data from Sheets and Harris (1965).

[3] Half-life.

Organic material (principally humus) is the major soil constituent that reduces leaching because of its strong adsorption. For example, sodium humate apparently adsorbs and solubilizes the non-polar compound 2,4,5-T from solution (Wershaw *et al.*, 1969). Organic material can adsorb most organic compounds from water; thus, in practice, phytotoxicity due to leaching is a rare problem even when water-soluble herbicides are applied to organic soil.

Herbicide (2,4-D) residues in the bottom muds of cold lakes or those with low oxygen contents may persist for 10 months (Smith and Isom, 1967).

Residues in Water

The herbicides most commonly used to control aquatic weeds are xylene, copper sulfate, 2,4-D, acrolein, endothall, and diuron (Anon., 1971). Few materials are registered for this use because of the potential environmental problems. The main sources of herbicidal residues in water are from direct application, aerial drift from application, runoff from land, and control of ditchbank vegetation (Frank, 1971).

Johnson *et al.* (1967) discussed the pesticide-residue-monitoring studies carried on by various U.S. agencies and concluded that a number of insecticides were important residue indicators, but none of these were herbicides. Eleven streams in the Western United States were monitored for nine insecticides, 2,4-D, 2,4,5,-T, and Silvex. No herbicide residues were found (Brown and Nishioka, 1967).

Dosages of most herbicides applied for aquatic weed control are initially on the order 0.1 to 4 ppm in water, except for aromatic solvents (xylene), which are as high as 600 to 700 ppm. The latter residues, however, are highly volatile and diminish rapidly in water. Residues of many herbicides are detectable (>0.1 ppm) for days and weeks after application in treated pond water but rarely exceed 0.5 ppm after a few days (Frank, 1971, Table 4). Fenac, 3-aminotriazole, and dichlobenil appear to be the most persistent (Grzenda *et al.*, 1966; Van Valin, 1966). Herbicide concentrations in excess of 0.1 ppm are seldom encountered in forest streams close to treatment areas, even immediately after spraying (Norris, 1971).

The determination of the half-life, or "disappearance rate," of herbicide residues in water varies considerably, depending on temperature, ultraviolet light, pH of the water, aeration, size and nature of the particulate matter in the water, amount of vegetation in water, surface-depth relationships of the body of water treated, and so forth. The half-life of chemical residues in water is not necessarily constant with time, but depends on the effects of various concentrations of the herbicide on degradative organisms and other factors.

A number of chemicals that are persistent in soil are less persistent in water due to the action of ultraviolet light. A herbicide that is resistant to degradation in soil, such as picloram, is more easily decomposed by sunlight in surface water: it has a half-life ranging from 2 to 41 days, depending on water depth, amount of sunlight, and water quality (Hedlund, 1970). More studies on various herbicides concerning decomposition by sunlight are needed to help calculate a half-life in water.

Residues in Air

Herbicide residues in air may be from three sources:

1. Spray and dust drift at the time of application (only 20 to 80 percent of the spray or dust dispersed in air may reach the target) (Norris and Moore, 1970)

2. Dispersal of herbicides on particles due to wind erosion after application

3. Volatilization from treated areas (soil, water, plants, etc.) or other areas contaminated due to the above three mechanisms.

Items 1 and 3 are most important.

Occasionally during periods of great winds, the accompanying dust storms may deposit herbicides presumably carried over great distances (such as from Texas to Ohio) on contaminated or treated particles (Cohen and Pinkerton, 1966). Even during normal weather, particulate matter suspended in air may adsorb volatile herbicides as it does DDT and lindane, and then be redeposited on bodies of water or on the ground by rain storms some distance from the original source of application (Abbott *et al.*, 1965). Particles from air have been shown to contain 2,4,5-T in amounts of 40 ppb (Cohen and Pinkerton, 1966).

To a lesser extent than drift, volatility may be responsible for considerable damage to sensitive nontarget plants surrounding the target plants. The presence of herbicides in air in Washington State has been studied with various salts and esters of 2,4-D (Adams *et al.*, 1964). The role of herbicide volatility is not well understood and is seen mostly when herbicide damage occurs to valuable crops. The volatility of 2,4-D varies greatly depending on its form. For example, the vapor pressure of the methyl ester is 100 or more times greater than that of 2,4-D (Hamaker and Kerlinger, 1969). The volatility of a given herbicide from various treated surfaces varies greatly depending on the weather, formulation, and adsorptive capacity of the surface from which the herbicide volatilizes. Generally speaking, soil and other surfaces that adsorb herbicides to the greatest extent allow the least volatility. Many soils lose a large percentage of an herbicide within a few hours or days by volatilization.

Little is known of the fate of herbicides or other pesticides in air except that they are rapidly diluted. The dilution factor is the main reason for difficulty in detecting herbicides in air since present analytical methods are not sensitive enough to detect the low concentrations.

Sunlight alters the structure of many pesticides, especially in the presence of moisture and particulate matter as occurs normally in air. Techniques for simulating these effects are not well established. Compounds such as 2,4-D have been reduced to polymeric humic acids similar to soil humic acids by both artificial light and sunlight (Crosby and Tutass, 1966).

ECOLOGICAL EFFECTS

Man controls his environment by employing different practices for managing his crops, roads, parking lots, houses, utilities, and so forth. These practices are bound to have an ecological impact on the environment. The purpose of this report is not to evaluate the success of these management programs but rather to focus on an investigation of the *unintentional ecological effects* that may result from employing herbicides as a tool in these management programs.

The desired effect of herbicides on target plants is to kill. However, this may not be accomplished totally, and the target plant may instead have an altered metabolism. This may also happen to nontarget plants and microorganisms in the treated area. Obviously organisms differ in their sensitivity to a toxic agent, and this sensitivity changes depending on the physiological state of the organism. The resulting difficulty in precisely predicting effects probably explains the contradictory claims regarding specific herbicide effects on various organisms (Pimentel, 1971).

Although herbicides are types of plant-growth regulators, their effect is not limited to plants. Some animal species are quite susceptible to the direct action of herbicides (Table 1). The mammal and bird species tested were relatively tolerant of herbicides, but in many cases fish were susceptible to dosages ranging from 0.010 ppm for trifluralin to 1000 ppm for chloramben.

A great range in susceptibilities is equally apparent among freshwater invertebrates (Sanders, 1970a and b). In tests of 16 herbicides against six species, dichlone was the most toxic. Species differences also were evident; for example, the 48-hour LC_{50} of dichlone (fungicide) was 0.025 mg/l for water fleas (*Daphnia magna*) and 3.2 mg/l for crayfish.

Tadpoles of *Bufo woodhousei* tested at 4 to 5 weeks of age showed 96-hour LC_{50} values of 0.11 mg/l for trifluralin, 1.2 mg/l for endothall, and 14 mg/l for paraquat (Sanders, 1967).

Chronic effects of certain herbicides on fish have been reported (Eller, 1969). Endothall (0.3 ppm) and potassium endothal (17.6 mg/l) produced ovalike cells in the testes of redear sunfish and bluegills. The incidence of the cells was related to duration of exposure.

Herbicides may also affect nontarget organisms within a target area, such as the microorganisms that are important in nitrification and degrading wastes. Audus (1970) concluded after a thorough review that herbicide pollution, at least presently, does not constitute a serious threat to soil-microbial equilibrium. He does note, however, rather large differences in response between different microbial groups. Bacteria may either increase or decrease in number, depending on whether they can utilize the herbicide as an organic substrate for growth. Nitrifying bacteria are, in general, tolerant of most herbicides. However, nodule-forming rhizobia associated with legume plants and cellulose-degrading microorganisms are sensitive, for example, to 2,4-D and fenuron, respectively (neither chemical is recommended for use on legumes). Malone (1972) reported that repeated applications of sodium cacodylate reduced species numbers and biomass in the community. He also noted that litter decomposition was rapid in the sprayed areas, and this diminished an important nutrient sink for the ecosystem. Sugar beets responded to a sublethal dosage of 2,4-D by increasing the level of potassium nitrate from 0.22 to 4.50 percent (dry weight), which later proved highly toxic when ingested by cattle (Stahler and Whitehead, 1950).

Herbicides may reduce or eliminate resistance in plants, rendering them more susceptible to attack by pests. For example, red clover and oat strains resistant to pest nematodes lost their resistance when exposed to low levels of 2,4-D (Webster and Lowe, 1966; Webster, 1967). Exactly how 2,4-D eliminated the resistance response in these crop plants is unknown.

Herbicides may alter the nutritional content of crops—either increasing or decreasing their food value. The protein content of oats, for instance, was increased with simazine (0.07 kg/ha) by 28 percent over untreated oats (Schweizer and Ries, 1969). However, beans grown as a second crop on previously treated soil were observed to have a lower level of protein than a control (Anderson and Baker, 1950). Also, there was an increase in the carotene content of carrots treated with linuron (Sweeny and Marsh, 1971).

Although little information is available, low levels of herbicides (2,4-D) seem to interact with air pollutants such as SO_2 and NH_3 to injure plants (Sherwood and Denisen, 1966); however, herbicide interactions with other chemicals may reduce herbicidal activity.

In other situations, serious insect-pest outbreaks may follow the use of herbicides, thus requiring the application of still more pesticide. Apparently, some weed killers alter the chemical makeup of the crop plants, making them more attractive and nutritious to insects which consequently become more abundant on the treated crop plants. Fox (1964), for example, reported that 2,4-D applied at a rate of 1 and 2 lb/acre increased wireworm damage to wheat (maximum dosage in the United States is 0.5 lb/acre). At a rate of 1 lb/acre, 31 percent of the wheat plants were damaged, whereas in the untreated check only 5 percent were affected. Putnam (1949) reported that the average number of grasshoppers per square yard was about double in plots treated with 2,4-D (1 lb/acre): 59 in plots treated with 2,4-D compared with 30 in the untreated control. The investigation did not establish whether the increase observed in plots treated with 2,4-D was due to nutritional or other changes in the plants.

Also, herbicides may indirectly stimulate the reproduction of pest insects. For instance, in bean plants exposed to sublethal levels of 2,4-D aphid progeny production during a 10-day period was increased from 139 to 764 per aphid (Maxwell and Harwood, 1960). Rice stalk borer larvae grew almost 45 percent larger (35.1 mg versus 24.4 mg for the control larvae) during the 30-day experimental period when rice plants on which the larvae fed were treated with 2,4-D (Ishii and Hirano, 1963).

In addition, insect-pest outbreaks may be caused by herbicides because beneficial insect predators are injured by the chemicals. Aphid outbreaks were reported on oats after the use of 2,4-D at a rate of 0.5 lb/acre because fewer predaceous coccinellid beetles were present and active in the crop (Adams and Drew, 1965). When applied at a rate of 0.5 lb/acre, 2,4-D killed up to 75 percent of the coccinellid beetles and extended the normal developmental time from 16 to 27 days (Adams, 1960). Moreover, their normal predation activity was depressed, making these beneficial coccinellid beetles less effective biological control agents (Adams and Drew, 1965).

Few quantitative studies have been made to ascertain the indirect effects of herbicides on the population sizes of nontarget organisms in a system. However, because of animal and plant interrelationships, we would expect the population sizes of nontarget species to be either increased or decreased after herbicide treatments. Moore (1967) indicates, for example, that the general reduction in the sizes of bird populations in England may be attributed in part to the reduction of shrubby roadside habitats by the use of herbicides. On the other hand, deer populations in California were increased as a result of herbicide use. In the latter case, the subsequent resprouting of killed shrub tops provided an increased food supply for deer (Krefting and Hansen, 1963). Herbicides have been used with striking success to control gophers by selectively killing their food source (Keith *et al.*, 1959).

Moore (1967) described how herbicides may be used to control the population size of a nontarget organism through rather indirect means. Partridge populations have declined in England due in part to a decrease in insects that provide their major food supply during their early life stages. The decline of the food supply is attributed to the reduction in the plant host of these insects through the use of herbicides. Such a chain of events is diagrammatically indicated in Figure 2. Partridge populations have declined in Germany apparently because herbicide use has reduced their food supply and shelter.

Pond ecology and production also can be affected by herbicide use (Simpson and Pimentel, 1972). For example, simazine applied to 0.25-acre ponds at the rate of 1 or 3 mg/l controlled the weed *Potamogeton foliosus* and all filamentous forms of algae for almost 5 months (Mayer and Mauck, 1971). It also lowered the pH of the water and drastically changed the species composition of bottom-dwelling invertebrates. Residues persisted for at least a year.

Although the potential for harm exists, a number of herbicides can be used to control weeds in aquatic sites without damage to fish and fish-food organisms (Walker, 1969a). For example, the sodium salt of dalapon (2,2-dichloropropionic acid) was not hazardous to fish and other aquatic animals at the recommended rate of 15 lb/acre. Diquat, which is recommended for controlling submerged weeds, algae, and floating aquatic plants, has a safe margin of toxicity to fish and fish-food organisms. Residues are rapidly adsorbed on clay and disappear from the water. Endothall (dipotassium and disodium salts) is recommended because it is relatively safe while controlling most species of submerged aquatic plants. The methyl alkylamine salts are much more toxic to fish. Trifluralin, in contrast, is one of the most toxic herbicides to fish, but under normal crop use there appears to be little danger to aquatic habitats.

Unfortunately, little is known about the natural controls of weed species, aquatic or terrestrial. Thus a given herbicide treatment may have unpredictable consequences. For example, residual herbicides utilized to control fall-germinating cheat-grass result in the elimination of this competitor to the spring-germinating sandbur, an equally undesirable weed. With the herbicide leached by winter rain and competition reduced, the sandbur evidently flourishes (Roche, 1967).

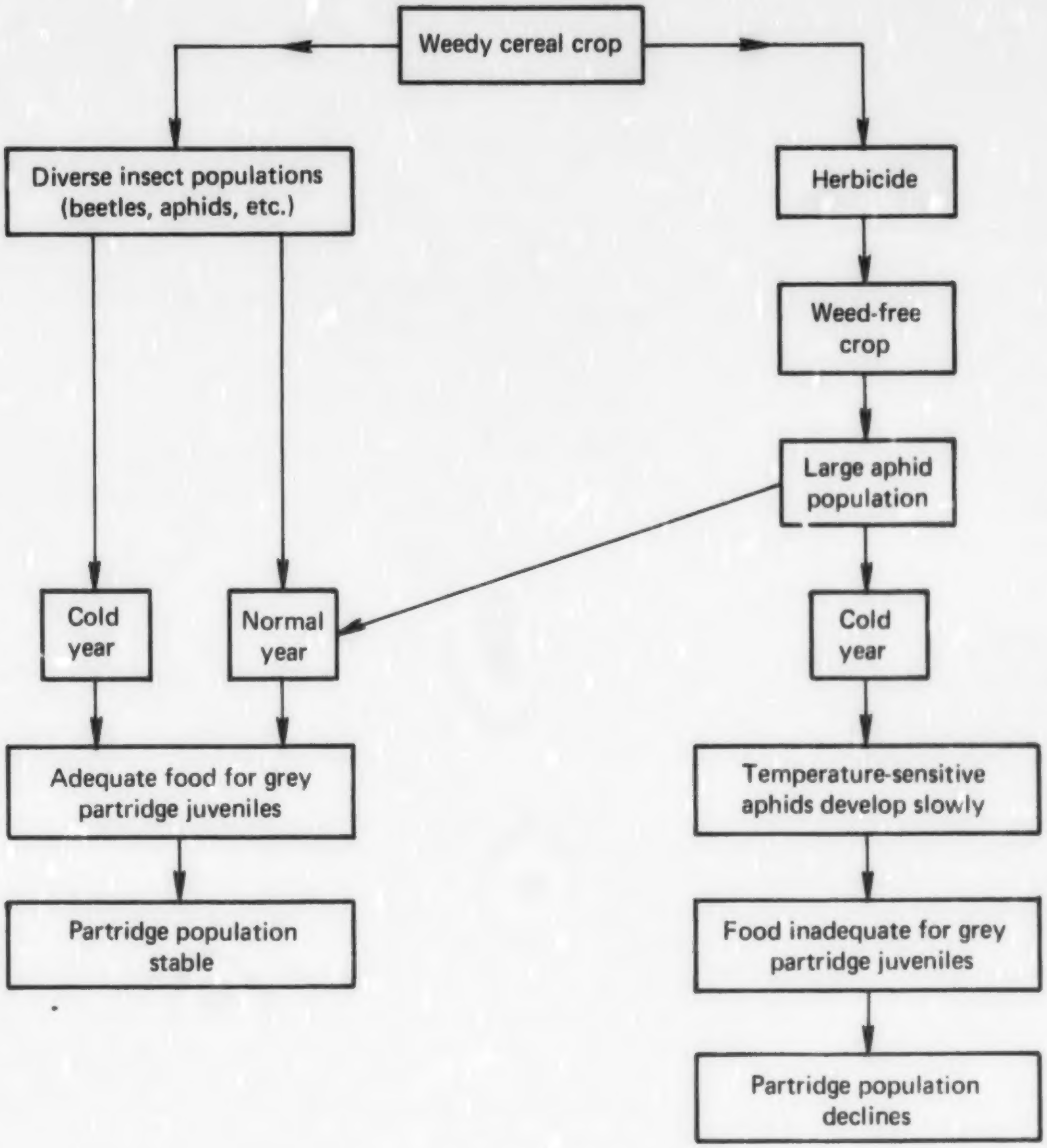
Weedy cereal crop
Diverse insect populations (beetles, aphids, etc.)
Herbicide
Weed-free crop
Large aphid population
Cold year
Normal year
Cold year
Adequate food for grey partridge juveniles
Temperature-sensitive aphids develop slowly
Partridge population stable
Food inadequate for grey partridge juveniles
Partridge population declines

Figure 2. Interrelationships between herbicide usage and the size of gray partridge populations in England (data from Potts, 1970)

ECONOMIC AND ECOLOGICAL CONSEQUENCES OF ALTERNATIVE WEED-CONTROL PRACTICES

Man controls weeds in crops, on industrial sites, and in aquatic systems as part of various management programs. This chapter explains only the economic and ecological consequences of weed-control practices employing herbicides or alternatives; it does not attempt to evaluate the overall wisdom of these weed-control programs.

Crop Weed Control

Of all the herbicides applied in the United States, nearly 70 percent is used on crop lands, and 85.2 percent of the land area treated with herbicides is crop land (USDA, 1971). Atrazine is the most widely used herbicide, and corn receives more herbicides (over 40 percent) than any other crop (Tables 3 and 4). Field crops, exclusive of pastures and rangeland, account for about 84 percent of all herbicides used in agriculture (USDA, 1970a). About 10 percent is used on pasture and range and the remaining 6 percent on vegetables.

Although weeds reduce crop yields, they can be controlled by chemical means, by mechanical cultivation, or by a combination of methods. Herbicide use on crops has increased because some state and federal agencies have urged farmers to use herbicides and because chemical control in some crops is more effective, economical, or convenient than mechanical cultivation.

Whether herbicidal or mechanical control is better depends on the particular crop, rotations, soil, weather, weed species, and other conditions. As an example, consider the use of herbicides versus mechanical cultivation in corn production. Corn is selected for this analysis because this crop receives 41 percent of all the herbicides used in agriculture (USDA, 1970a). Weeds in corn can be effectively and economically controlled by herbicides alone, by mechanical cultivation alone, or by a combination of both methods. The factors that influence the choice of weed-control method are discussed below.

Effectiveness.—Depending on weather, weed species, soils, and cropping systems, either herbicidal control, mechanical control, or a combination may be more effective (Meggitt, 1960; Drew and Van Arsdall, 1966; Armstrong *et al.*, 1968; Buchholtze and Doersch, 1968). For example, under wet conditions herbicides may be more effective than mechanical cultivation; under dry conditions, however, mechanical control may be more effective. The trend toward using a combination of controls for weeds, according to Slife (1972), is the increased use of early-planted corn that utilizes the full growing season, thus increasing yields. Planting in the Corn Belt about May 1 with the long-growing varieties means that field conditions are wet and cool; hence there is a need for herbicidal weed control in early spring.

Economics.—Depending on the weather, weeds, and labor availability, economic returns may be highest in corn production employing herbicides, mechanical cultivation, or a combination for weed control (Drew and Van Arsdall, 1966; Armstrong *et al.*, 1968; Slife, 1972). The costs of controlling weeds in corn with herbicides (two applications of herbicide) range from $10 to $14 per acre; costs for mechanical cultivations (three cultivations) range from $3 to $4 per acre. Often a combination of herbicide and mechanical cultivation gives higher corn yields than either one alone; sometimes economic returns are also higher (Drew and Van Arsdall, 1966; Armstrong *et al.*, 1968; Buchholtze and Doersch, 1968; Slife, 1972). For one companion crop of corn (soybeans), four herbicide treatments cost $25 per acre for the growing season, whereas four cultivations cost $12 per acre (Hauser *et al.*, 1972). Hauser *et al.* also reported that mechanical cultivation resulted in slightly higher soybean yields; however, Slife (1972) found that higher soybean yields were obtained with a combination of herbicide and cultivation than with cultivation alone (control with herbicide alone was not tested). For another companion crop (wheat), the use of one herbicide treatment did not increase yields over those obtained without a herbicide (Slife, 1972).

Table 3. USE OF FOUR MAJOR HERBICIDES AND ALL HERBICIDES ON CROPS IN THE UNITED STATES IN 1966[1]

Crop	2,4-D		Atrazine		Trifluralin		Randox CDAA		Total[2]			
									Four major herbicides		All herbicides	
	1000 pounds	1000 acres	1000 pounds	1000 acres	1000 pounds	1000 acres	1000 pounds	1000 acres	1000 pounds	1000 acres	1000 pounds	1000 acres
Corn	14,701	22,411	21,066	13,740	6	10	3893	3034	39,666	39,195	45,970	44,175
Wheat	6,851	13,733	11	13	--	--	--	--	6,862	13,746	8,247	16,657
Other grains[3]	4,131	8,053	2	3	--	--	--	--	4,133	8,056	4,921	10,155
Pasture and rangeland	9,122	6,745	1	3	--	--	--	--	9,123	6,748	10,506	8,055
Cotton	250	175	--	--	2631	3552	--	--	2,881	3,727	6,526	7,166
Soybeans	103	231	61	26	2238	3050	954	673	3,356	3,980	10,409	10,997
Total all crops	35,158	51,348	21,141	13,785	4875	6612	4847	3707	66,021	75,452	86,579	97,205
U.S. total	39,513	56,893	23,495	14,978	5184	6953	4898	3721	73,090	82,545	112,420	111,801

[1] Source. *Quantities of Pesticides Used by Farmers in 1966* (USDA, 1970a). The data given are for active ingredients.

[2] Some duplication of acres occurs when more than one herbicide is used on the same acreage or when the same acreage is treated more than once with the same herbicide.

[3] Includes oats, mixed grains, barley, and rye.

Table 4. ESTIMATED ACRES TREATED WITH SELECTED MAJOR HERBICIDES IN THE UNITED STATES, 1966-1969[1,2]

Type of use	2,4-D	2,4,5-T	All phenoxys	Picloram	Cacodylic acid	All non-phenoxys
Agricultural	56,893 (39,513)	3451 (1655)	62,454 (43,235)	118 (81)	101 (3)	49,337 (69,185)
Lawns and turf	1,200	1200 (600)	3,433	(3)	(4)	1,371
Rights-of-way	3,000	2175 (4368)	(5)	(4)	(4)	(5)
U.S. Government	1,149 (2,225)	296 (656)	(4)	12 (16)	23 (156)	(4)
Private forests	(4)	430 (888)	(5)	(4)	(6)	64
Aquatics	(4)	81 (162)	199	(3)	(3)	17
Other	(4)	306 (583)	1,521	(4)	(4)	139
Total nonfarm	(24,387)	4488 (7257)	(4)	(4)	(4)	(4)
Total all uses	(63,900)	7939 (8912)	(4)	(4)	(4)	(4)

[1] Source: Anonymous.

[2] Data given in thousands of acres. The numbers in parentheses are thousand pounds of active herbicide materials used.

[3] Less than 500 acres treated.

[4] Not available.

[5] Included in other uses.

[6] Not registered for this use.

Insects and Diseases.—As already indicated, herbicide treatments may cause outbreaks of insect and pathogen pests, which in turn may require insecticide treatment. Such outbreaks take place because the crop plants lose their natural resistance to pests after herbicide treatment, because the plant becomes more nutritious for the pests, or because some natural enemies of the pests are destroyed. Recent investigations have shown that aphids increase twofold on corn exposed to 2,4-D (0.25 lb/acre), and this same treated corn was significantly more susceptible to corn smut disease (Oka and Pimentel, 1974). Oka (1974) has also found that European cornborer larvae tend to grow larger on 2,4-D exposed corn than on untreated corn and that exposed corn is significantly *more* susceptible to corn leaf blight.

Pollution.—Herbicides may pollute the surrounding environment by drift during application and by either volatilization or runoff after application. The volatilization of 2,4-D, for instance, may injure sensitive plants in the near vicinity of the treated area. The problem of herbicide runoff depends on the slope of the land (White *et al.*, 1967) and whether the herbicide has been worked into the soil. In addition to the dangers of direct runoff, silting is a problem. When herbicide treatments are used, water runoff is greatest if no cultivation is used because the upper soil layer is relatively smooth and closed. In contrast, with mechanical cultivation the upper soil layer is kept broken and open, thereby facilitating the penetration of rainwater into the ground and the conservation of soil.

In addition, pesticide pollution effects may be increased because herbicide use may create new pest problems that require additional pesticides (see "Crop Rotations," below). Although the difference is small, weed control with herbicides may require less energy (calories) than mechanical cultivation. Based on the estimate that about 22 gallons of gasoline are used per acre of corn (Pimentel *et al.*, 1973) it was found that about 2 gallons are used per acre for three cultivations (about 72,450 kilocalories per acre). The application of 2 pounds of preemergence and 2 pounds per acre of postemergence herbicides requires about 80,225 kilocalories per acre (11,000 kilocalories per pound of herbicide plus 1 gallon of gasoline for two applications).

Moisture and Land Conservation.—As mentioned, rain penetrates easily into mechanically cultivated soil, thus conserving moisture. To determine whether plowing, no plowing (no tillage), cultivation, or no cultivation is most effective in promoting moisture conservation is a complex problem. Blevins *et al.* (1972) reported that with no-tillage culture of corn more moisture was recorded in the upper 0- to 8-centimeter soil layer than with normal plowing. However, Drew and Van Arsdall (1966) reported that with herbicide control the upper layer of soil was more compact than with mechanical cultivation, and therefore there was greater moisture loss with herbicide control because the capillary action was unbroken without cultivation. Hence the question of moisture conservation remains unclear.

Herbicides, as mentioned, increase the yields of some crops and may release some land from crop production. It has been estimated that if herbicides were not used and substitute practices employed, losses due to weeds might increase from 8.5 to 10.2 percent (USDA, 1965; USDA, 1968; USDA, 1971; Pimentel, 1973). To make up this difference in crop production would require as much as 2.3 million additional acres. Hence an estimated 2.3 million acres are probably released from crop production and are available for other purposes.

Crop Rotations.—Weed control with herbicides may either reduce or prevent the rotation of corn with crops of oats, soybeans, and other nonhosts of corn pests because of the hazards of herbicide residues for these susceptible crops (Knake and Slife, 1962; Wisk and Cole, 1965; USDA, 1968; Swain, 1970; and Burnside *et al.*, 1971). As a result, there may be an increased tendency to grow corn on corn, and this may increase insect, disease, and weed problems. For example, a pest problem that may occur from repeated corn croppings is the corn rootworm (Tate and Bare, 1946; Hill *et al.*, 1948; Metcalf *et al.*, 1962; Ortman and Fitzgerald, 1964; Robinson, 1966). The resulting rootworm problem may require the use of additional pesticide (insecticide) for control. This contributes to pollution and increases the overall costs of pest control.

Tradeoff of Herbicides and Price Supports.—The price-support and land-retirement program encourages intensive agriculture. This may include using herbicides and other pesticides because increasing yields have to be obtained on fewer and fewer acres. At the same time, crop-production restrictions on previously productive lands may result in the culture of some corn on less fertile land on a national basis, thereby increasing the production costs of the crop (Heady *et al.*, 1972; Pimentel and Shoemaker, 1974). Price supports and the land-retirement program cost the nation nearly $5,000,000,000 during 1969 (USDA, 1970b). A careful analysis of the advantages of not restricting the production of corn and other crops on some of the most fertile land of the nation is needed. An analysis is also needed to determine the costs, benefits, and risks if mechanical cultivation were substituted for herbicides in crop production. For example, based on the best data available, it is estimated that it would cost $500,000,000 annually to substitute mechanical control practices for control with herbicides in all crops (USDA, 1971; Pimentel, 1973).

Conclusions.—Each particular crop situation and weed, insect, and disease control problem must be evaluated based on solid economic and environmental analyses. Agricultural crop production can more effectively meet the double challenge of increased production and decreased pollution by adopting a systems approach to crop management. Based on this approach pest control becomes an integral part of the total crop-management program. This type of pest control requires an understanding of the basic ecological mechanisms affecting the crop and the interactions of such diverse factors as the pest, crop, water, soil, pesticides, fertilizers, rotations, sanitation, and other cultural practices. Additional inputs in the analysis include economics, public health, and the environmental impact of the system as a whole. With this approach, sound decisions about weed-control measures are based on an analysis of the total costs and risks and the total benefits of all factors interacting in the system.

Industrial Weed Control

Herbicides are used to control vegetation in many situations not directly associated with agricultural crops. Major nonagricultural uses include the management of vegetation on roadsides, rights-of-way, transmission lines, fire breaks, and parking areas. Of the total land area treated with herbicides in the United States, 14.6 percent consists of rights-of-way and similar brush- and tree-habitat areas (USDA, 1972). Rights-of-way alone amount to over 60 million acres (Niering, 1967). Brush, trees, and other vegetation may interfere with transmission lines, block views, hinder passage along roadways, or restrict other activities on rights-of-way. The largest industrial use of herbicides is for brush control under transmission lines.

Brush and young trees can be effectively controlled by herbicides or by mechanical means alone. When the concept of management is substituted for the concept of control, prescriptions can be written to achieve the desired effect, and these prescriptions can include mechanical methods, herbicides, or both. The factors that determine the choice of weed-control method are discussed below.

Effectiveness.—In extremely rough terrain, where it is impossible to use tractors and other heavy mechanical control equipment, herbicides are almost a necessity. On flat terrain, if only grass cover is desired, mechanical means may be equally effective.

Economics.—Depending on the terrain and availability of labor in a region, weed control is generally less expensive with herbicides than with mechanical means. Employing 2,4,5-T, brush control on transmission-line rights-of-way costs about $6.50 per acre, whereas mechanical control costs about $44 per acre (Office of Science and Technology, 1971). However, the costs of using other herbicides run only slightly below those of mechanical control, or $42 per acre for brush control. Selective basal spraying is possible at essentially the same costs as blanket spraying. Along road rights-of-way, herbicide control costs about $9 per mile per year, whereas mechanical control costs about $16 per mile per year (McQuilkin and Strickenberg, 1962).

Animal Life.—In the management of rights-of-way, repeated blanket spraying produces and maintains low ground cover. Selective basal spraying, however, produces a habitat of maximum diversity, maintaining a variety of shrubs and herbs that produce fruit and seeds and attract a varied animal life. Retreatments are needed much less frequently than with blanket spraying, and costs are therefore essentially equal over a period of years (Svenson, 1966). This approach is no longer a theory; it has had an adequate test by several commercial companies in the East (Hall and Niering, 1959) and is widely used by some of them as standard practice (Potomac Electric Power Co., 1964).

Pollution.—Herbicides may pollute environments adjacent to treated rights-of-way by drift during application and by volatilization or runoff after application; the principal problem is drift. Because rights-of-way are normally a few hundred feet wide and extend for many miles through wild habitats, the potential for polluting adjoining habitats is great.

Runoff.—The elimination of some vegetation with herbicides may expose portions of the soil to runoff and soil erosion. Since many grasses cover the bare areas quickly, this condition lasts only a part of a season. With primarily a grass cover, the water yield measured in stream flow from the treated watershed areas may be increased as much as 80 percent (USDA, 1970c). Although mechanical control may result in reduced runoff in some cases, running tractors over the soil may leave wheel tracks that collect water and eventually result in small washed-gullies.

Conclusions.—Management practices for woody-plant control that bare the soil in rights-of-way are detrimental in the long run. Through the judicious use of selective herbicides, total ecosystems can be maintained.

Aquatic Weed Control

The management of aquatic plants by chemicals constitutes an ecological manipulation that is more difficult to control and assess than the management of terrestrial plants. There are two principal reasons for this. First, natural waters constitute an active transport system; even the waters of an apparently quiet pond are in motion due to changes in temperature, wind, evaporation, and inflow. A flowing stream carries chemicals far from the site of application in a very short time. In the estuaries, the ebb and flow of tides facilitate the movement of chemicals. Second, the complex and variable ecological systems of ponds, streams, and estuaries are at the base of a pyramid of aquatic and terrestrial life whose ramifications cannot readily be traced. At present the kind of alterations produced by herbicide use can be judged only in part.

Of the total area of the United States treated with herbicides, 0.2 percent is aquatic habitat areas (USDA, 1972). Herbicides are used in aquatic habitats to control vegetation for better recreation, including fish and wildlife management (DeVaney, 1968; Walker, 1969b). Herbicides are also used to control weeds in navigable channels and other waterways. Such treatments have resulted in drastic reductions in the kinds and numbers of aquatic plants and animals, including fishes.

The most common herbicides used for the control of aquatic weeds are xylene, copper sulfate, 2,4-D, acrolein, endothall, and diuron (Anon., 1971).

Weeds in recreational waters and irrigation canals can be effectively controlled by herbicides, mechanical means, and water-management practices. An analysis is made here of the advisability of employing various weed-control techniques on recreational waters because this is a major use of aquatic herbicides. Some of the factors influencing the desirability of employing one practice or a combination of practices are discussed below.

Effectiveness.—For macroscopic plants either herbicides or mechanical means may be effectively employed for aquatic weed control; however, microscopic plants like algae can be effectively controlled only with herbicides. In some unique situations, aquatic weed problems might be effectively controlled by management of the water system, which might involve diverting sewage, removing nutrients, or changing water levels.

Economics.—Weed control under aquatic conditions is costly whether herbicides or mechanical means are used. For example, the control of weeds in a recreational lake (Chautauqua Lake in New York) cost an estimated $45 per acre ($37 for herbicide plus $8 for application) with herbicides and $50 per acre (all costs, including hauling the weeds out of the lake) with mechanical means (Weaver, 1967). Although mechanical control was slightly more costly, it had the important advantage of removing the weeds (including polluting nutrients) from the lake (see "Eutrophication," p. 74). Feeding tests with cattle using dried, pelleted aquatic weeds have indicated that some aquatic weeds were as good as alfalfa in both palatability and nutritive qualities (Vietmeyer, 1972). Hence, if weeds can be used for animal feed, aquatic weed control by mechanical means could be more profitable than control with herbicides.

Fish.—For some weed problems, like the water-hyacinth, control may increase the fish population for sport. However, in other situations, reducing aquatic weeds may result in reducing the populations of game fish such as bass and trout.

Pollution.—Acute and chronic toxic effects on certain species of fish and fish-food organisms may occur after the use of herbicides. Another obvious secondary effect that results from the rapid kill of aquatic vegetation is oxygen depletion. This is a more serious problem with herbicides than with mechanical controls because herbicidal control can be carried out more rapidly and over extensive areas. The long-term effects of habitat change on the aquatic system are not easily appraised and because of this are generally unknown.

Eutrophication.—The most important reason for increased aquatic weed problems in recreational waters today is eutrophication, or the enrichment of lakes and rivers with nutrients, primarily nitrogen and phosphorus. The sources of nitrogen are agriculture and urban and rural sewage, whereas the source of phosphorus is primarily sewage. Aquatic weed problems could be substantially reduced if the sources of nitrogen and phosphorus could be limited. Mechanical control has an important advantage over herbicidal control in that nitrogen and phosphorus are removed in the weeds provided they are transferred completely from that ecosystem.

Conclusions.—Aquatic weed control is difficult, costly, and sometimes a problem environmentally with either mechanical means or herbicides. The use of herbicides presents an additional potentially dangerous factor. This can best be summarized by a statement from the National Academy of Sciences 1968 report:

> Although safe levels of more than 100 herbicides alone and in combination have been tested for effects on fish production in aquariums for up to three years, factors involved are so complex that data are inadequate to conclude whether a herbicide that is nontoxic to fish will interfere with fish reproduction when applied at the lowest rate needed to control weeds in a given body of water.

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AGRICULTURAL AND OTHER APPLIED USES

FINDINGS

Forest Management

1. *Herbicides are one of many management tools available for improving yields from commercial forest lands.* The economic consequences of no management of forest lands are severe. Original cutting may leave undesirable species which remain dominant thereafter. The use of least disturbing practices tends to promote forest stability with minimum loss due to erosion and nutrient leakage.

2. *Herbicides are the most selective method (other than hand labor) of eliminating shrub or cull-tree species to enhance desirable forest growth.* The beneficial effects of properly applied herbicides outweigh the risks. The benefits from herbicide use span many years, whereas the risks are short-lived because herbicide residues dissipate in a period of months, or less. The effects on habitat, desirable or undesirable, depend on the original habitat condition.

3. *Herbicides can be applied with minimum damage to our natural resources when used properly.* In forestry, herbicides are generally applied by aircraft. By careful application, the subsequent movement of herbicides can be controlled. Drift can seriously damage susceptible nontarget organisms. There is evidence that fish and food-chain organisms have not been seriously affected by the level of phenoxy herbicides contaminating streams. Occupational and personal health risks are minimal.

Grazing Lands

1. *It is impossible to control weeds on grazing lands without some ecological impact.* The purpose and primary impact of weed and brush control is to change the vegetative composition of the grazing site from brush and weed to "grassland," which may be a subclimax vegetational type. Since residues are relatively short-lived in soils and dissipate rapidly from animal tissues, they are not concentrated in the food chain.

2. *Aerial spraying is the only practical means of herbicide application on the more extensive brush-infested ranges and pastures.* While mechanical methods are used where applicable, they are usually expensive, relatively nonselective, often less effective, and often must be accompanied by reseeding.

3. *Because of herbicides' selectivity, the nontarget species of plants that are not killed increase in size and cover coincident with the slow death of unwanted species and thus continuously provide more cover for wildlife species, and more protection against soil erosion than other methods of control.*

Aquatic Uses of Herbicides

1. *In all but a few instances, the efficacy of herbicides has exceeded that of presently available alternatives for aquatic plant control.* Mechanical methods will continue to be employed where applicable or in sensitive areas. A few species may be controlled with biological control agents but there will have to be continued heavy reliance on chemical techniques as a part of the total technology for controlling aquatic and ditchbank weeds.

2. *Intentional modification of aquatic habitats affects wildlife in various ways.* Complex ecological systems may undergo far-reaching changes not yet fully elucidated by research. Food plants and nesting sites may be degraded. Conversely, thinning or modification of aquatic weeds may improve such sites and reduce potential oxygen depletion when overabundant plants die and decay.

Herbicides in Crops

1. *Worldwide losses from weeds, due to reduced crop yield and quality, together with the cost of weed control, amount to 10 to 15 percent of the total value of agricultural and forest products.* During the last 20 years, the use of 2,4-D to control weeds on an accumulated total of 460 million acres of wheat increased the yield by about 2 billion bushels—enough wheat to supply each American family with over 6 years' supply of bread. Chemical weeding permits simplification of crop rotation, avoidance of soil disturbance, adjustment of row spacing to the optimum for each crop, mechanization, and economy of labor.

2. *There is no evidence that agricultural uses of herbicides cause an accumulation of residues in humans, domestic animals, or wildlife.* Evidence from monitoring studies indicates there is little overall buildup of residues in soils; persistence is relatively short. Major herbicide problems have been drift to nontarget species, some instances of persistence in soil, and contamination of waters.

3. *In crop production, the use of herbicides, along with other weed-control methods, has not only reduced labor input and cost of production, but has increased yields.* For example, in the past decade the amount of hoe labor for cotton production in certain areas of the United States was reduced from 48 to 13 man-hours per acre by the use of herbicides. The cost of labor for weeding strawberries decreased from as much as $200 to as little as $16 per acre where selective herbicides were used in combination with tillage. A significant portion of the 900-lb.-per-acre increase in rice yields in the United States from 1961 to 1969 resulted from improved weed control through the increased use of herbicides. This increase in yields represented a dollar value of approximately $90,000,000 for 1969 alone.

4. *The ability to control weeds is as important to the individual grower of minor acreage crops (e.g., asparagus and berries) as to the grower of major acreage crops (e.g., corn and cotton).* With the current increase in total registration requirements, few herbicides will be developed for the producer of minor crops. The manufacturer's economic return from the sale of a herbicide for a minor crop use does not warrant the cost of development of registration information. A procedure must be developed whereby growers of minor crops may be assured of the continued development of improved herbicides for their needs.

The term "minor crops" has been misleading. A newer term—"minor uses"—more clearly defines the problem. Now that registrations must be for specific weed-crop situations, a particular use where the volume of herbicide does not justify the cost of registration should be considered a minor use.

5. *In fruit and nut crops, the cost of hand labor has become almost prohibitive on a commercial basis.* In certain orchards mowing is effective. Increased growth and yields result from herbicide use in conjunction with mechanical weed-control techniques.

Industrial Weed Control

1. *On some industrial sites where weed control is required, nonchemical weed control methods may be used effectively. On other industrial sites, herbicides are the only practical method.* The need for visibility, accessibility, moisture conservation, fire-hazard control, and the prevention of vegetation fouling are some of the factors which may require weed and brush control. Hand-labor costs and

steep terrain may prevent the use of nonchemical methods. Some drift and leaching potential, erosion, and reduction of animal cover may result from certain applications of herbicides.

FORESTS

The Forest as a Resource

Approximately 500 million acres of the continental United States are commercial forest land. The timber growing on this land constitutes the major renewable source of raw material for fiber and shelter. The annual production of some 50 billion board feet of timber from these lands has a direct annual value of over $5,000,000,000 and a substantially greater value when considering the secondary industries this supplies.

It is evident in considering our forest-resource statistics, together with the histories of European nations supporting commercial forests, that the forests of the United States can continue indefinitely to produce raw materials at the existing rate. Capacity exists for substantially increased production, but the present condition of these forest lands with respect to weeds imposes an upper limit on the amount that can be cut without a further deterioration in quality (USDA, 1965; Newton, 1973a).

Forests are important areas for the management of wildlife, water supplies, and various other nonsalable byproducts. Nontimber values, especially those related to recreation, are increasing at a rapid rate. Qualities that make a forest attractive for lumbering (i.e., high quality, large trees, and good access) also make it attractive for recreation. The forest owner or manager in meeting his social responsibilities must maintain the nontimber values while relying solely on timber for operating revenue. His ability to maintain all values depends on his success in replacing trees currently being harvested and keeping these stands in good condition.

The forests of the United States are in various conditions. The hardwood and coniferous forests of the East have been heavily cut over, with regrowth mostly of inferior species and forms (USDA, 1965); the coniferous forests of the West are generally in better condition. Unfortunately, the inventories of American forests do not reflect directly the potential for improvement in productivity. Comparisons of average forests with those under ideal management always provide an overly optimistic estimate of the values that can be achieved by management. Actually we should be receiving a much greater yield from most of the commercial forest lands in this country. It was estimated that 26 percent of the commercial forest land, or 114 million acres, was poorly stocked or not stocked at all with commercial species in the 48 states inventoried in 1953. At that time resource inventories indicated that a "reasonable" level of management would double the growth of timber to 100 billion board feet per year (USDA, 1958). Walker (1973) indicated that 300,000,000 acres of commercial forest land are producing at less than 70 percent of their potential in native species, with losses attributable to weeds only. Most of this potential can be achieved by the restoration and maintenance of original species composition on cutover lands. The same practices would also improve the status of the nontimber resources in both the long and short run.

Many management tools are available to forest managers for achieving yields of whatever commodities are desired from commercial forest lands. Nearly all involve replacing undesirable vegetation with desired tree species. Herbicides are just one of many tools that can be used to suppress the undesirable species. Herbicide use must be evaluated, however, in comparison with the comparable features of alternative methods. Such a comparison is the purpose of this guide. As a technical supplement, the March 1973 issue of the *Journal of Forestry* was devoted almost entirely to this subject.

Unique Features of Forests Under Management

The major differences between annual croplands and forests are the result of the difference in time during which the crop accumulates. Forests, in general, retain large amounts of naturally occurring soil nutrients in the living vegetation and litter. They also sustain a highly complex system of secondary organisms that depend on forest production for their sustenance. Soil-profile development, with its substantial layer of litter and humus, provides a tree-dependent soil-fungi complex that is unique. Similarly, such soil development maintains a substantial community of insects and worms that is largely confined to forests although not unique to them. Wildlife habitat provided by forests is unique in the sense of providing cover along with a supply of undergrowth for forage.

Unique as forests are from the standpoint of biological structure, many of our croplands were once forests and differ only in having been deforested. Many of the cleared lands abandoned in past economic crises have been reinvaded by forests with no appreciable loss of productive potential. Thus the outstanding characteristic of a forest is the dimension of a time sequence in which various life systems can develop. Such time dependency in forest-resource management places stringent economic constraints on operating alternatives.

The primary producers of a forest, principally the dominant trees, control the local forest environments. The length of time needed to grow trees to 75 percent of their mature size ranges from 30 to over 150 years. Investments in forest management therefore carry a very large interest accumulation. Thus forest environmental management investments must be made far in advance of harvest, with costs kept to an absolute minimum.

The public has a major stake in the resource dominated by such trees. The landowner is asked by the public to maintain the resource. Yet the public is also involved in an economic system that taxes a salable tree every year and offers alternative investments that encourage timber owners to cut all salable trees and invest the income elsewhere. Under the circumstances, the public has a clear responsibility to support the development and implementation of forestry practices that preserve resource values economically but will not cause more harmful effects than the practices they replace.

The Forest as a Dynamic System

The time dependence of forest life-support systems bears careful analysis. Trees must grow in order to live. Most of the commercial timber species need to be the largest individuals in a forest to avoid being shaded out of the stand. As juveniles they may be crowded out by more successful plants that may or may not have some value in management. The forest manager, regardless of management objectives, must ensure that desirable species have access to sufficient resources to continue growing indefinitely. Whether a plant is removed by herbicides, by wildlife browsing, or by harvesting another plant will replace it (Newton, 1973a). In general, the more violently one disturbs a forest, the more rapidly the forest structure changes after the disturbance. After clearcutting or scarification with a bulldozer (analogous to ploughing a field), weeds, shrubs, and noncommercial trees grow in profusion together with seedlings of commercial species. Resources are usually fully utilized by plants within a very short time after such disturbance, and individuals of many species sustain heavy mortality through crowding. When commercial species are jeopardized by other plants, the forester employs various management tools to ensure that growth resources continue to be available for the species he wishes to grow (Gratkowski, 1967).

Not all of the forester's tools involve such drastic disturbances as clearcutting or scarification. Selective felling, single-tree poisoning, and selective spraying are all far less destructive than complete scarification in preparation for planting. Because they make fewer changes in stand structure, organisms dependent on forest structure are displaced less. Moreover, the use of the less disturbing practices tends to promote stability of forest composition with a minimum of losses due to erosion and nutrient leakage. The theory of forest dynamics under manipulation has been outlined by Newton (1971, 1973b).

History of Forest Exploitation

Most of the commercial forests of the United States have undergone a history of exploitation, some for as long as 250 years. The hardwood forests of the East, especially, have been subjected to chronic removal of the most desirable trees. The trees remaining, after the best trees have been harvested, make up increasingly defective forests. Many areas of the Eastern United States support forests that are growing perhaps one-half or two-thirds as much total wood as their productive capacities would suggest. In addition, the value of the wood and the condition of the wildlife habitat are very severely impoverished by poor species composition (Benzie *et al.*, 1973; Fitzgerald *et al.*, 1973). Thus, although forest-inventory statistics imply that forests are growing more wood than is being harvested, these figures do not indicate that the quality of wood is being maintained or even that the products that are growing are more than marginally utilizable (USDA, 1965).

The condition of the forest is worst in the most poverty-stricken areas of the United States. Over 100 million acres in Appalachian and southern hardwood regions are capable of supporting very high quality raw material in forests, yet they are producing at a small fraction of their potential (USDA, 1965). High-quality raw materials are desperately needed for economic stability. Incentives for forest improvement both for industrial raw material and for wildlife habitat are needed badly. Because such vast areas are involved and because the economic consequences of *no* action are so severe, appropriate tools must be available to land managers for forest improvement. The degree to which the tools are appropriate must be given careful scrutiny.

Operating Premises and Management Alternatives

Every forest-management operation has both ecological and economic implications. The issues involved in regulating forest practices are viewed very differently by the voting majorities, on the one hand, and by private forest owners and public land managers on the other. Several operating premises that related to the fundamental decision processes involving herbicides can be outlined. Since these are based on certain value judgments, they are arguable. They do, however, make possible some comparisons of alternatives on the tactical, rather than the strategic, level; it is at this level that the decision between herbicide and nonherbicide methods may be made rationally.

Premise I: Once-productive forests that for various reasons have little prospect of restoration to desirable composition and form without man's intervention justify such intervention.

This premise assumes the following:

1. The environmental impact of mismanagement still persists on such lands, and restoration toward original species composition is a means of removing an existing undesirable, manmade condition.

2. Forest rehabilitation is needed only once in any given stand since desirable composition can be maintained by continued appropriate management.

3. A base for forest production is needed indefinitely.

4. Forest resources of all kinds can be maintained with the least adverse effects if the broadest possible resource base is under management.

5. Steps taken to improve the resource base must be planned in advance of product need, ranging from a few years in the case of wildlife to 80 years or more for optimum timber or recreation use.

The issue of whether wild land should be placed under management is not involved here, since the effects of poor management are already prevalent in forests justifying treatment. Thus, the choice is whether management is to revert to and maintain original composition or to permit continuation in shrub or cull-tree cover abnormal to the site. Once the management objective has been decided on, an approach toward implementation can be outlined. The question of herbicides can then be considered in relation to alternative methods directed toward the same objective.

Approaches to Forest Rehabilitation.—The goal of forest rehabilitation is to grow desirable species. Two general approaches are common, depending on the initial presence or absence of desirable trees. Where stands contain enough desirable trees, but undesirable trees prevent them from becoming dominant, they do not need planting. Site resources, being preempted by undesirable plants, can be made available to the desirable trees by removing undesirables, and desirable vegetation can then become dominant. This condition is common in eastern hardwood forests. In the other situation, very common in coniferous forests, sites occupied by undesirable vegetation to the exclusion of desirable trees require provision for establishment and maintenance of the trees as well as vegetation removal. The newly established trees must be provided adequate site resources continuously for several years to prevent excessive mortality. In both cases rehabilitation involves the provision for adequate numbers of desirable trees to occupy a site and for allocation of site resources in their support.

In all forest ecosystems the dominant vegetation controls the availability of site resources (Newton, 1973). Both of the above approaches involve treatment of vegetation to redistribute resources between desirable and undesirable forms. Stands with desirable trees already established do not normally require treatments having prolonged direct effects; establishment of trees from seedlings requires longer periods of control.

The methods of releasing resources for tree growth all involve removal of associated plants. The elimination of certain plants influences resource supplies for trees; it also affects food supplies for insects, birds, and mammals. How the plants are killed affects the quality and quantity of regrowth and the physical environment in which it is growing. The degree of physical disturbance also determines the extent of physical injury to wildlife and habitats, as well as exposure of soil to weathering and erosion.

Vegetation-control practices entail either physical violence or toxic action. Most forest-rehabilitation operations involve some of each. Given a land area in need of treatment, the choice of methods includes only those with some objectionable features. The decision of whether to treat is likely to be based on costs of undesirable side effects balanced against returns and desirable side effects. The choice of method involves costs, expectation of success, and impact on resource values in addition to timber. The following discussion of methods includes various chemical and nonchemical techniques. Because this is a guide for chemically oriented decisions, emphasis is on chemical methods; nonchemical tactics are considered as counterparts only sufficiently to identify their role as alternatives to chemicals. Both groups of methods are discussed according to their economic and ecological impacts when applied with adequate provisions for achieving comparable objectives.

Before considering methods in detail, nontimber values of forests must be considered in relation to timber management. Timber is the primary revenue-producing forest product. Management for optimum timber production, however, has multiple effects on wildlife, water quality and yield, and aesthetics. These effects are likely to be interpreted differently in long- versus short-term evaluation. In many instances, enhancement of one value is offset by a decrease in another. For example, management of primary forest tree species in long rotations to enhance recreation opportunity has the positive effect of providing large trees, eagle perches, and attractive scenery and the negative effects of poor forage for big game and low return on investment (Black, 1974). Details of value changes and tradeoffs are discussed under premise II. The following discussion covers ecological effects of both groups of methods. Specific chemicals and their properties are reviewed under premise III, relating to environmental hazards and management alternatives.

Forest Practices Toward Rehabilitation.—Rehabilitation involves the establishment of trees and practices that guarantee their continued survival. The following discussion of practices assumes that provision has already been made for stocking of trees and that cultural treatment is in support of plantation survival. It also assumes that ecological analysis has identified vegetation and vegetation-dependent factors as being the primary obstacles to stand development.

Chemical Control.—Herbicides are one of several groups of important tools in vegetation management. Of the various plant-killing methods, they are the most selective, they alone have biological effects persisting after treatment, and they exert their effects without violence. They achieve their effects exclusively through toxic action on sensitive plants. This is done with more or less no effect on resistant species, depending on the degree of resistance, and negligible toxic or physical injury to mammals under operational conditions, as far as is known (Norris, 1971).

Chemical practices have been developed to divert to trees resources tied up by several groups of competitors. They have also been used to eliminate various nonvegetative pests that are present in response to certain ecological conditions (Lawrence, 1967; Laird and Newton, 1973; Newton and Holt, 1971). These practices accomplish their objectives through the natural tendency of plants to utilize available resources; suppressing various plant groups leaves resistant plants more free to grow. Suppression of all vegetation, without the provision for species capable of using the released resources, may cause loss of such resources, especially nutrients (Likens *et al.*, 1970); such practices are not recommended in constructive forest management.

Chemicals used to control forest vegetation generally have a short life. Their direct effects are almost exclusively confined to plants in the sense that known toxic levels to mammals and other wildlife are much higher than those encountered in their use operationally (Warren, 1967). Their direct effects on plants cause an important restructuring of species abundance among plants.

The effect on animal habitats is great (Lawrence, 1967). Whether this is beneficial or detrimental depends on the condition of the habitat initially and the desirability of gains or losses among various animal species. The restructuring of dominance in the plant community is deliberately aimed at encouraging desired species, generally with the objective of permanent change. Thus the life of the *effect* of the herbicide is much greater than the life of the *chemical* in the environment. All organisms dependent on primary producers are affected by change in cover, regardless of whether chemicals have been used to effect the change.

The use of chemicals to control certain groups of plants has some unique features:

1. All herbicides used in forestry are selective in some important way.

2. Herbicides do not cause physical injury to preestablished trees, resistant plants, animals, or soils.

3. Herbicides usually have minimal impact on water quality, with no siltation problems nor complete exposure of water to sun.

4. Chemical control leaves protective cover for wildlife while frequently enhancing the nutritive value of resistant plants and pioneer species.

5. Dead plants may temporarily constitute a continuous fuel supply in some circumstances; hence herbicides may increase the fire hazard briefly.

6. Certain herbicides may influence the metabolism of some plants and thus make them more or less vulnerable to pest activity.

7. Aerially applied herbicides may not respect boundaries.

On balance, herbicides are a very potent tool in ecosystem management. They permit the accomplishment of forestry tasks that would be postponed indefinitely if mechanical or labor-intensive methods had to be used. The important advantage that herbicides may be applied quickly may, however, allow errors of planning or application that are not identified until the job is complete. Like any other tool, they are subject to misuse and must be carefully controlled.

Mechanical Control.—Mechanical control as discussed here relates to practices involving power equipment for vegetation control. These are used primarily where total vegetation eradication is desired; occasionally, selective felling is used where desirable trees are established, as in precommercial thinning.

Control is achieved by uprooting, chipping, or knocking down vegetation. The least intensive practices involve bulldozers that flatten woody plants without removing them. The most intensive includes chopping of brush and incorporating the chopped material into the soil. All practices of this type leave the site in a less disturbed condition than does an agricultural plow, but in a substantially more disturbed condition that that produced by herbicides alone.

Comparison between mechanically and herbicidally prepared sites indicates that they do not accomplish the same thing in the short term, but they may both support the same long-term objectives. Mechanical clearing exposes mineral soil extensively. Mineral soil provides seedbeds for abundant herbaceous growth as well as woody plants. The mixture of herbs and shrubs tends to compete severely with planted trees and to provide abundant forage. In the presence of adjacent cover, the habitat for deer is one that supports maximum numbers of animals. The effect of animal use is frequently so severe as to stabilize cover, including planted trees, in a browsed-down, pasture-like condition. Enhancement of deer habitat, however, is accompanied by changes in cover for many small mammals, hares, and rabbits. Some species may benefit; some may decline (Lawrence, 1967; Borrecco, 1973).

Mechanical methods have both advantages and disadvantages. Any conventional bulldozer can do the job, but some special equipment can improve efficiency. Physical obstacles to reforestation are removed, which reduces problems in planting operations (Bentley, 1967). The results of the operation are easy to perceive: no toxic substances are involved. The most serious disadvantages are those of physical disturbance and cost. If total ecosystem impact is considered, this practice may have important effects on virtually every component. Whether these effects are judged to be beneficial or detrimental depends on management objectives. The exception to this is the increase in soil mobility associated with scarification. In addition to erosion potential on steep slopes, soil redistribution may also cause local nutrient deficiencies.

The disturbance of surface soil creates a receptive seedbed. In some areas rapid revegetation is needed for surface stabilization; in others competition and animal use are excessive. Achievement of exactly the appropriate amount of cover is very difficult to manage.

Fire.—Removal of vegetative competition by burning is an important practice in forestry, especially in the Southeastern United States. Periodic burning is a natural phenomenon in many lightning-prone areas. Under evolutionary pressure, fire-resistant species (e.g., southern pines) were naturally abundant primarily because of repeated fires. Exclusion of fire has led to increasing abundance of ground cover and decreasing regeneration (USDA, 1965). Maintenance of conifer forests has come to depend very heavily on the control of hardwoods, with fire, herbicides, or mechanical eradication being the predominant tools.

The utility of controlled fires depends on accumulation of fuel and suitable burning conditions. The fire must consume the fuel, yet do so with an intensity that does not damage the trees. This requires burning every few years to avoid fuel buildup; no other practices depend on repetition in this way.

The unique effects of fire as a vegetation control method include the following:

1. Fire favors the survival of heat-resistant trees and the germination of seeds stimulated by heat.

2. Fire eliminates accumulations of fuel without soil disturbance, provided slopes are moderate and fire intensity is low.

3. Burning of forest debris releases some nutrients for rapid uptake by pioneer vegetation; the resulting growth tends to be lush and of high nutritive content for wildlife.

4. Fires tend to cause violent death to certain groups of nonburrowing animals, even though survivors may have a substantially improved habitat.

Some of the above features are important in the applications of fire as a substitute for herbicides or other control techniques. Problems of smoke control, animal escape, and national antipathy to forest fires limit free use, however. Furthermore, the prevention of fires for extended periods allows fuel to accumulate through natural processes, so that controlled burning is no longer feasible in many areas.

A new application of fire involves a combination of herbicides and fire. The so-called brown-and-burn technique is sometimes used for preparing a total brushfield for planting. The method allows for the desiccation of fuel without the physical disturbance of bulldozing or cutting. When the green brush has dried out, it can be burned when burning conditions on unsprayed areas prevent spread outside the prescribed area. This practice has the advantages of both burning and herbicides. Applied in small units, it has the advantages of allowing animal escape, incinerating residual herbicides, and reducing smoke emission. Cost, in general, is equal to or less than that of scarification, and there are instances where the prospect of plantation survival and growth are close to optimal for this technique.

No Vegetation Control.—Commercial forest species almost invariably cast sufficient seed to provide for adequate regeneration. The presence of several million acres of unregenerated cutover land in the Douglas-fir region alone is testimonial to the stability of untreated vegetation that has been allowed to develop to the exclusion of conifers. Gratkowski *et al.* (1973) have identified vegetation in the forms of herbs, shrubs, and noncommercial hardwoods as responsible for extensive regeneration failures. Of five major timber-producing states in the East, land supporting well-stocked stands of desirable species accounted for only 1 to 9 percent of commercial forest area, whereas 69 to 86 percent of the forest area was occupied by trees of marginal value. On most of this, only planting or stand conversion will improve production status (USDA, 1965). Prospects for natural reemergence of native coniferous forest types are virtually nil within the lifespan of a human being. The unpromising status of the hardwood forests in the Eastern United States is due to a history of selective cutting that has left mature trees of no value (to the owner) to form the dominant forest cover. This condition is virtually permanent, in the context of present economic models, without some cultural practices to restore original composition.

Forest-inventory data for forested regions of the United States describe a reasonably large growth for the poor hardwood forests of the East. They also point out that much of the wood is of poor quality and marginal salability (USDA, 1965). This consequence of "no control" provides abundant evidence that *not* killing undesirable plants has a prolonged economic and ecological effect. Nearly all the lands so described once supported valuable stands. In no documented instance has a history of "high-grade" harvesting of trees decreased the productive capacity of the land. Thus the consequences of no control are not reflected in the productive capacity of the land, but only in the utility of the existing tree cover and the long timespan involved in natural reversion to original conditions.

Environmental Perspective of Control Practices—Do They Accomplish the Same Thing?—The choice among alternative methods of vegetation management has implications from the standpoint of both intermediate and end objectives. Chemical and nonchemical controls function in different ways. They have in common only the killing of above-ground portions of undesired woody plants to promote growth of some desirable vegetation. If both methods succeed in establishing their objective vegetation type, they have both achieved their long-term goals on a similar basis. In the short term, however, there are consistent differences.

Typically, herbicides do not eradicate all woody plants. The mixture of living and dead plants provides abundant food and cover for big and small game, and adequate perches remain for predatory birds. Eventually, crop species become dominant, and the game habitat is then controlled by the ability of understory forage species to persist under crop-tree dominance. Changes in species composition are achieved without physical disturbance either to animals or soil. At no time is the living complex of plants so completely suppressed that nutrient losses are likely, although complete eradication does carry this hazard (Likens *et al.*, 1970). Fears of toxicity to animals appear to be unwarranted when herbicides are used as recommended (Brown, 1967; Norris, 1971).

The achievement of long-term goals by the physical removal of vegetation has a substantial disrupting influence on an ecosystem. The soil is disturbed and may be compacted by working moist soil. Animal habitats are more completely changed than they are when herbicides are used, but forage is still greatly increased for some species and decreased for others. The microenvironment for planted tree seedlings is characterized by more sunshine, more herbaceous competition, and more severe moisture stress. The enhancement of seedbed conditions for shrubs and herbs sometimes results in the establishment of a competitive cover that requires herbicide treatment to release trees from suppression by competitors. There is no toxic effect from physical removal. However, the physical disturbance has a greater total impact on animal life than does the use of herbicides.

In perspective, the preceding comparisons of physical and chemical removal of vegetation may be viewed in relation to ordinary agricultural practice. The act of plowing and growing an agricultural crop repeatedly constitutes a chronic maintenance of ecosystems in a disturbed state. None of the forest practices maintains the chronic stress; the long-term objective of rehabilitation is, in effect, to relieve stress. The infrequency of herbicide application or related forest practices and the low percentage of total forest area that will ever be re-treated under management indicate the limited nature of the national scope of problems resulting from the use of herbicides for forest rehabilitation. However, the long-term effect of not using herbicides or other rehabilitation methods will be widespread and will downgrade both economic and aesthetic values.

Premise II: Forest practices supporting the management of any specific resource should be considered relative to their impacts on other uses and values.

This premise is based on the following assumptions:

1. The public has an interest in the long-term perpetuation of all forest-resource values.

2. Long-term considerations outweigh short-term expedience in resource management.

3. The economic return from the dominant forest use(s) may be necessary to maintain the entire complex of forest resources on any given ownership.

Approaches to Resource Management Relevant to Herbicides.—Every forest practice has some impact on all forest values—some positive, some negative, and many so small as to be insignificant. Impacts are viewed differently by owners and nonowners, depending on economic interests and personal points of view. In forests, especially, nonowners are prone to pass judgment on management and to consider mismanagement by their own definitions a public issue. Private ownership accounts for nearly three-fourths of the commercial forest land in the United States. The issues related to the long-term maintenance of resources on all forest land are of public significance. Those related to forest management within the confines of specific ownership and not affecting long-term resource maintenance are largely of personal or academic interest. This discussion therefore presents the impacts of forest practices relative to their duration and according to classifications that can be separated according to their public or personal significance.

Table 1 illustrates the effect of tree establishment and maintenance practices on various public and private forest-resource values. Timber is the primary economic value to the private owner; water quality and yield are of general public interest but of little economic importance to private owners. Game resources are of interest to the public, but on private lands game resources are only tolerated by the owners. Aesthetic values are of general interest, but they may actually be of negative value to private owners because of their effects on valuation and taxation. Thus the regulation of practices to a particular end is likely to increase values to one interest group at the expense of another. The effect of regulating practices so that the owners' forest-management options are reduced is likely to have a long-term effect on resource values of all kinds; departure from forestry uses of land will have a greater impact than will almost any of the methods used in the perpetuation of forests. Much of the pressure to regulate is from the urban-oriented public. Responsiveness to such pressure can be adequate only if there is a reasonable understanding of tradeoffs involved in any action.

The listing of impacts in Table 1 includes reasonable generalizations. Exceptions can be made to some of them on an individual basis, which is merely evidence of the great variability of forest conditions within this nation. Such exceptions are attributable, in part, to unusual environmental conditions requiring special management. More frequently, the exceptions result from the misapplication of a soundly advised practice. Such exceptions can occur with every practice, however, and are perhaps less likely to occur with herbicidal than with nonherbicidal methods.

Premise III: Long- and short-term hazards to the environment are significant in any selection among forest-management alternatives.

The term "hazard" is defined here as opportunity for damage to environmental factors and values. In this discussion the following assumptions are made:

1. Hazard is real only under circumstances where a practice sets up a condition where damage can occur as a direct result and where the probability of such damage is great enough to justify concern.

2. Choices among management alternatives all involve choices among hazards, with none of the alternatives offering a no-hazard choice.

3. Priorities in methods, and hence in hazard selection, are based on human safety, resource maintenance, economics, and extra-management fringe benefits, in that order.

Herbicide-related hazards will therefore be discussed in terms of the usage of the various types of chemicals, the behavior of the same compounds in the forest system, and the relation of hazard associated with such behavior to hazards related to nonherbicidal methods.

Herbicides Used in Forestry.—The enormous range of job specifications for herbicides requires a broad range of chemical properties. Basically, these compounds can be classed according to usage, persistence, and relative toxicity. They are used as soil treatments, foliage sprays, or injection fluids. Persistence ranges from moderate to short in the general context of pesticides. The toxicity of most herbicides used in forestry is in the range of moderate to low (Warren, 1967). Many materials are useful for more than one purpose, particularly those suitable for injection and foliage application. The general characteristics discussed below are consistent within forest-use classifications.

Table 1. COMPARATIVE ENVIRONMENTAL IMPACTS OF FOREST PRACTICES AND THEIR DURATIONS[1]

Practice	Timber values	Water quality	Water yield	Big game	Small game	Aesthetics	
						Hiking	Highway travel
Tree planting[2]	Great (+) (if successful) Long	Small Long	Small Long	Great (–) Long	Great (–) Long	Great (+) Long	Great (+ and –) Long
Vegetation control:							
Chemical:							
Herbs	Great (+) Long	Small (–) Short	Small (+) Short	Moderate (–) or (+)[3] Short (+) Long (–)	Moderate (–) or (+)[3] Short and long	Small Short	Small Short
Brush	Great (+) Long	Small (–) Short	Moderate (+) Short	Moderate to great (+) Short	Variable Long	Attitude dependent (–) Short	Attitude dependent (–) Short
Weed trees	Great (+) Long	Small Short	Small Short	Small to moderate (+) Short	Small (+) Short	Small to moderate (–) Short	Small to moderate (–) Short
Mechanical:							
Herbs	Moderate (+) Long	Moderate (–) Short	Moderate (+) Short	Great (+) Short	Variable to great (–) Short	Moderate to great (–) Short	Small to moderate Short
Brush	Great (+) Long	Moderate to great (–) Short	Moderate (+) Short	Variable (+ and –) Short	Great (–) Short	Attitude dependent Short	Attitude dependent Short
Weed trees	Great (+) Long	Small Short	Small Short	Moderate (+) Short	Small (+) Short	Small to moderate (–) Short	Small to moderate (–) Short

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[1] Plus or minus relates to a presumed value change relating to a specific resource.

[2] Impact of planting depends on success, which in turn may be determined by the effectiveness of cultural measures.

[3] Selectivity range of the herbicide will determine whether residual vegetation provides a more or less favorable habitat.

Compounds used specifically for their soil activity tend to be low in water solubility and are prepared for this use largely as wettable powders or granules. They are suspended in water or applied dry. Those in general use are nonvolatile and are nearly immobile in soil. All are low in toxicity to mammals and have half-lives of 1 to 6 months (Anon., 1972).

Foliage-active materials include almost all other compounds used in forestry. They may be either soluble or emulsifiable in water. Those that emulsify in water are generally completely soluble or miscible in oil. Many that are soluble in oil are neither emulsifiable nor soluble in water and are formulated specifically for oil-borne bark sprays. The addition of an emulsifier may make them directly comparable to any other emulsifiable material of other similar properties. Water-emulsifiable herbicides may be mixed with either water or oil, or a mixture of oil and water. Water-soluble compounds are almost never miscible or emulsifiable in oil and are used solely in water. These compounds range from moderately volatile to nonvolatile and from moderately leachable to tightly adsorbed. Persistence is variable, with the reported half-lives ranging from 1 week to 6 months. Toxicity to mammals ranges from moderate to low (Anon., 1972).

Herbicides formulated for injection must be water soluble. These materials are used as undiluted concentrates and are usually provided with surfactants that cause them to soak into a moist woody surface exposed by a fresh cut. Virtually all of these herbicides have foliage activity; a few are used on soil or foliage and as injection fluids. These materials are generally used in a manner that isolates them from the general environment in reforestation. Persistence in this isolated application is not known, nor is the hazard to mammals.

The compounds discussed below are grouped and described in relation to forestry use. This material was abstracted from Newton (1969) and the *Dictionary of Pesticides* (Anon., 1972).

Soil-Active Compounds.—Amizine is a mixture of amitrole (3-amino-1,2,4-triazole) and simazine (2-chloro-4,6-bis(ethylamino)-*s*-triazine) in the ratio of one part amitrole to three parts simazine. Its uses and application rates are similar to those for atrazine, except that amizine has more ability to suppress established perennials, including desirable species exposed to the spray.

Atrazine (2-chloro-4-ethylamino-6-isopropylamino-*s*-triazine) is used in early spring at rates of 3 to 5 pounds of 80 percent product per acre in 5 or more gallons of water. This compound is very selective in confier plantations, even when applied broadcast after planting. Atrazine is the most common herbicide used for herbaceous weed control in conifer plantations. Very popular with Christmas tree growers, it often produces rapid growth and a deep blue-green color in conifers. Atrazine may be mixed with 2,4-D, with general broadening of the weed-control spectrum. Its residual activity is generally limited to one growing season. It can cause damage to crop trees in light soils and with heavy rainfall.

DCPA (dimethyl tetrachloroterephthalate) has little general use for field application in forestry. In some experiments it has been shown to have good selectivity for weed control in nursery beds.

Fenuron (3-phenyl-1,1-dimethylurea) is the only common forest-brush-control herbicide that depends exclusively on soil activity. It has been used with success particularly on moderate- to coarse-textured soils in plantations of southern pines. It selectively kills hardwoods in southern pine plantations. Its residual activity may last more than 1 year.

Dalapon (2,2-dichloropropionic acid) is the only water-soluble, soil-active compound in common use for herbaceous weed control in forestry. It is used as a grass killer in plantations at rates of 4 to 10 lb/acre. It is often combined with triazines and 2,4-D. Dalapon has a short residual life and has low mammalian toxicity.

Simazine has uses similar to those for atrazine, except that it has a much lower solubility, is more strongly adsorbed in the surface soil, and is less effective on resistant perennials. Generally, simazine requires heavier rates of application than does atrazine (3 to 8 lb/acre) and is more expensive than atrazine for any given degree of weed control. However, simazine may be somewhat more selective at high dosage rates than atrazine. Some residual activity may be observable 1 year after application. It is well suited for light soils in areas of high summer rainfall. Toxicity to mammals is low.

Substituted uracils, carbamates, and many other soil-active herbicides are not applicable for general use in forest plantations. Local trials may demonstrate selectivity sufficient for economic, safe weed control in particular combinations of soil, vegetation, and crop species. Since many such compounds have not been tested in forestry, their potential is not known.

Foliage and Stem-Applied Brush Killers.—Amitrole has an action unique among the brush killers. Its uptake is mostly through foliage, and its action is through the destruction of chlorophyll material in the tissues of weed leaves. Amitrole is necessarily applied during the foliage season—and in a water carrier. It is frequently used at rates of 1 to 4 lb/acre in 10 or more gallons of water. Amitrole is extremely effective against certain shrub species, particularly members of the blackberry group. It has the drawback of being quite damaging to most conifers, although selectivity at rates of 1 to 1.5 lb/acre has been found. Its degradation in the soil is rapid. Although low in acute toxicity, amitrole has been reported to have carcinogenic properties.

Ammate (ammonium sulfamate), as distinguished from the fertilizer ammonium sulfate, has an extremely high degree of toxicity to plant foliage. It is relatively nonselective and kills weeds and brush alike through foliage uptake and translocation. Common solutions for use involve 1 to 4 pounds of ammate per gallon of water applied to the point of dripoff. Notwithstanding its general effectiveness, this material is quite expensive for general broadcast herbicide use. It is highly corrosive, low in toxicity, and has a short residual life.

Brush killer is a half-and-half mixture of 2,4-D and 2,4,5-T used to control general mixtures of brush species. The mixture is cheaper than 2,4,5-T alone and is effective on some species that are sensitive to 2,4-D without the high cost of the 2,4,5-T spray. It probably does not have a much broader range of action than 2,4,5-T alone, but its use is frequently justified on the basis of cost. It has not always been observed that the 2,4-D and 2,4,5-T actions are fully complementary (see 2,4-D and 2,4,5-T for specific behavior).

Picloram (4-amino-3,5,6-trichloropicolinic acid) has extreme foliage activity in woody plants. Effects are produced through root uptake; it is also used for injection. It is capable of controlling many species resistant to 2,4-D and 2,4,5-T. Its cost is high, however, and its residual action on conifers can be detrimental. It is nonselective in mixed conifers and hardwoods. Special techniques for application must be devised before picloram can be generally recommended for use in forests. It is formulated in ways similar to 2,4-D or 2,4,5-T. The solvent in which it is used is usually water. The rates of application are normally 0.5 to 2 lb/acre for general brush control in a low volume of water or up to 2 pounds per 100 gallons in a broadcast high-volume treatment. Picloram is classed as moderately persistent, with residual effects persisting 6 to 12 months. It is one of the more mobile herbicides in soil, although damage resulting from mobility appears to be limited with forest applications. It is low in acute mammalian toxicity.

Silvex [2-(2,4,5-trichlorophenoxy)propionic acid] is very closely related to 2,4,5-T and is used in some situations where species resistant to 2,4,5-T are the dominant brush species. Its superiority to 2,4,5-T for multiple-species control has not been amply demonstrated, and the merits of Silvex over 2,4,5-T are usually insufficient to justify the additional cost. When used as a basal spray, in an oil solution, Silvex is specifically active against maples and perhaps other species. Its persistence and toxicity are slightly greater than those of 2,4,5-T; rates used are the same.

2,4-D (2,4-dichlorophenoxyacetic acid) is normally formulated as an amine, emulsifiable acid, or ester for effective brush-control work. This material is effective against many broadleaf herbs and some susceptible trees and shrubs like alder and willow. 2,4-D is low in cost and is high in effectiveness for susceptible species. In addition to its effectiveness on brush, it is also highly effective for increasing control of broad-leafed herbs not killed readily by atrazine. 2,4-D is damaging to conifers during the growing season, but not during the dormant season at moderate rates. Some pines are sensitive during early spring, particularly with oil solutions or emulsions. For broadcast application 2,4-D is usually used at rates of 0.5 to 4 lb/acre, depending on sensitivity of weeds and methods of application. During the dormant season the ester formulation is usually dissolved in oil or suspended in an oil-water emulsion for brush control and emulsified in water alone for herbaceous weed control. Amine formulations are used undiluted for injection of some species, but seldom for brush killers. The residual life of 2,4-D is short; the toxicity is moderate. Some esters are especially toxic to fish.

Very similar to 2,4-D in its action and uses is 2,4,5-T (2,4,5-trichlorophenoxyacetic acid). This material is more effective on many hard-to-kill woody species than 2,4-D; rates used are comparable to those of 2,4-D. Some species not controlled by either compound separately are killed by a mixture (brush killer). 2,4,5-T by itself and in mixture with 2,4-D is the most common phenoxy herbicide in use for general brush control in reforestation. Many forest species are not controlled at all well by 2,4-D, and the use of 2,4,5-T is advised where such 2,4-D-resistant species are common and where they interfere with forestry objectives. The residual life of 2,4,5-T is intermediate between that of 2,4-D and picloram, although activity in soil is slight. Acute mammalian toxicity is moderate; some esters are especially toxic to fish.

Herbicides Best Adapted for Injection.—Cacodylic acid (dimethylarsinic acid) is used to control conifers and numerous phenoxy-resistant hardwoods. Recommended rates are from 0.25 to 0.5 gram per inch of tree diameter, formulated as a concentrated salt solution. Cacodylic acid is thought to metabolize into materials that are apparently toxic or disagreeable to insects, and the incidence of insect attack following treatment with this material is less than would be expected for trees felled with a power saw. This material is subject to seasonal variation in effectiveness, with optimum use during seasons when most nonarsenicals are ineffective. Cacodylic acid is tightly bound to organic material and soils. It is not known how long it remains in the ecosystem, but there is evidence that it becomes biologically inactive within days. Microbial degradation has been reported, but kinetics are not yet known (Newton and Holt, 1971; Woolson and Kearney, 1973). Acute mammalian toxicity is moderately low.

MSMA (monosodium methanearsonate) is used in a manner similar to cacodylic acid for tree injection work. This material has shown greater activity than cacodylic acid on several species; it appears to be metabolized in the same way. The presumed metabolite may also be involved in suppression of insects in treated trees. MSMA has the advantages of low cost and of activity on some hardwoods for which cacodylic acid is not specifically active. It can also be used for chemical debarking and preharvest timber drying. MSMA is thought to behave in a manner similar to cacodylic acid; both are of moderate toxicity. The organic arsenicals may well provide opportunities for noninsecticidal control of bark beetles in conifers (Newton and Holt, 1971) and for nonfungicidal control of some root rots (Laird and Newton, 1973). These properties are probably unique to these herbicides.

Picloram is used for injection in conifers and in maples for both stand improvement and precommercial thinning. This material is mobile in the soil and in the translocating tissue of the trees; it is known to travel through root grafts and via exudation into the soil. Treatment of one species may promote the development of symptoms in other species. Picloram controls a broader spectrum of species by injection than any other known compound, and some drawbacks to its use may be justified on account of extreme effectiveness under some conditions. Picloram is used at low dosage rates for tree injection.

2,4-D amine, the common agricultural chemical used for killing dandelions and other sensitive weeds, is appropriate for spring and summer injections in oaks, willows, and alders. In contrast to the ester formulations, which are used for foliage and stem sprays, a water-soluble amine is essential for proper uptake and translocation after injection. 2,4-D amine is not effective in some species like conifers and maples. This material is always used undiluted. Effectiveness is greatest during the period of full leaf, although it is sometimes effective for winter usage. More injection is done with 2,4-D amine than with all other compounds combined.

2,4,5-T amine is comparable to 2,4-D amine in formulation. This material is more effective on some woody species than 2,4-D. Its superiority to 2,4-D is limited, however, and it is not widely used because of cost.

Application Techniques.—Herbicide application methods in forests have some unique features. Broadcast treatments are often applied by special equipment adapted for tall-brush or drift control. Individual tree treatments are found only in forestry practices; such treatments are necessary for killing large cull trees not killed by aerial treatment and for individual-tree selection for stand improvement.

Broadcast.—Broadcast applications of herbicides include coverage of the crop species. Volumes of 1 gallon to several hundred gallons per acre may be applied, but special equipment is required to get good coverage with volumes below about 10 gal/acre. Very low volumes require extremely small droplet size and high concentrations of active ingredients, a combination that lends itself to extreme drift hazard. Inherent in the high drift potential is the loss of herbicide before it reaches its target. This factor tends to discourage the use of very low volumes except in special circumstances. On the other hand, the excessively high volumes create serious problems of supply and excessive runoff of active ingredients. Volumes of less than 5 and more than 20 gal/acre are seldom applied aerially; ground rigs usually apply 100 gal/acre or less. Most broadcast sprayings of herbicides used in forestry are applied aerially in areas remote from croplands.

Treatments of Individual Trees.—Chronic difficulty is experienced in controlling large cull hardwoods in forests. Basal treatment has been one of the most effective and consistent methods of killing such trees. Backpack sprayer equipment is used, and treatments are applied simply by spraying around the basal few inches of the trees. A soaking solution of ester formulations of phenoxy herbicides in diesel fuel is usually used. Picloram has recently become available in ester formulations; this procedure is costly but effective. There are no known hazards other than those in handling the herbicide concentrates.

Concentrated herbicides may be used in small quantities in spaced cuts made in bark of trees. Cuts into which the herbicide is placed may be made with special tools or injectors. Injectors may take the form of hatchets or long hypodermic-type instruments with chisellike bits on the lower ends. Hatchets and oil cans are suitable for small jobs with a low investment, whereas injectors improve the speed of operation considerably when many trees are to be treated or the terrain is difficult.

Improvements in chemical technology have now provided a wide selection of compounds suitable for injection. Some of these compounds are so effective that very small volumes in widely spaced cuts provide adequate tree-killing capacity. The small volumes of herbicides necessary to accomplish a given job with injectors mean that refills are infrequent and labor costs for transporting materials are minimal. Tree injection lends itself well to precommercial thinning, hardwood control, and stand-improvement treatments in which both conifers and hardwoods may be controlled in the same operation. Amounts of herbicide used are small, and general environmental contamination is avoided with this method. Injection is presently the most selective and appropriate method for widespread forest-weed problems in the United States.

Hazards of Herbicide Use.—Herbicides are biologically active compounds. Despite their extreme activity in plants, however, their toxicity to insects, mammals, fish, and birds is usually much lower than that of insecticides. In terms of their effects on wildlife and fish, most herbicides should not be classed with the extremely toxic pesticides about which considerable alarm has been raised. Their relative safety notwithstanding, it is difficult to control the distribution of herbicides by aerial application. The rough topography common in forest areas tends to reduce the precision of application. Herbicides, although not normally toxic to mammals, come in contact with various organisms, including people. The effects of such contact warrant attention.

Stream Contamination.—Herbicides used in large quantities on large areas of forest land may find their way into watersheds. Considerable research has been conducted to determine the amount of herbicide present in streamflow at a given time after aerial application of herbicides over a stream. It has been found that direct application to the water surface is necessary for appreciable amounts of herbicide to get into streamflow. Even when open streams flow through spray-project areas, the degree of contamination is minor, particularly when the application falls on fast-moving water (Norris, 1967). Exclusion of open watercourses or streams 10 feet wide or more should ensure adequate safety, especially during the dormant season. Water usage from streams exposed during the growing season warrants close attention, however.

The amount of contamination from small streams receiving direct spray is very small and persists only briefly. Studies in the Pacific Northwest indicate that broadcast application during the dormant season is likely to produce peak concentrations in open waters, within projects, ranging below 1 ppb per pound of phenoxy herbicide per acre for each percentage of the watershed treated (Norris, 1967). There is no evidence that fish and food-chain organisms suffer seriously from phenoxy herbicides as applied in forest spray operations. Even in the summer, when streams are moving slowly, the main factors to be avoided are spraying directly into ponds, pools in slow-moving streams, and long, continuous stretches of open water. Such conditions are encountered infrequently in midsummer in the forest, however, and hence contamination tends to be a very localized problem. The maximum stream contaminations reported in forest spray operations have been substantially lower than published median tolerance limits for fish; furthermore, such concentrations are also observed to be short in duration (Tarrant and Norris, 1967).

In connection with 2,4,5-T, dioxin is a present concern. The present industry standard of a dioxin concentration of 10^{-7}, combined with normal operational stream contamination of 10^{-8} or less of 2,4,5-T as a maximum, indicates a peak dioxin concentration of 10^{-15} or less.

Livestock and Herbicide Residues.—Many herbicides used in forestry are permissible for use on agricultural crops on a "no-residue" basis. Farmers have expressed concern that livestock would stray on sprayed lands with the subsequent possibility of condemnation of meat. This problem is of special concern on open-range lands in the Western United States.

Most herbicides are metabolized readily or eliminated by livestock. Cattle and deer eliminate herbicides of the phenoxy and triazine groups without obvious toxic symptoms, when the herbicides are administered at dosages equal to or greater than those to be expected from browse in treated forests (Newton and Norris, 1968; St. John, 1964). Detection methods have become so sensitive, however, that minute amounts of herbicide may be detected now that were not detectable when the no-residue limit was originally established. Such residues are not construed as harmful, but should be recognized in terms of joint responsibilities of forest and livestock owners.

Drift Damage.—Herbicide movement through the atmosphere from a treated zone to sensitive crops and ornamentals has been a serious problem in agricultural operations. Many of the broadcast herbicides are applied in forests during the dormant season, when very few crops are sensitive. Nevertheless, aircraft normally fly higher in forest operations than over croplands, with an increased probability of drift of vapors and fine droplets. During seasons when crops or ornamentals are subject to damage, forest operations can cause drift damage at considerable distances. Much work has been done to reduce the likelihood of occurrence, however, and methods have been developed for drift management. The following steps will minimize the expectation of drift damage:

1. Spray near agricultural lands during the *dormant* season when possible

2. Ensure that the operation is well flagged

3. Never apply herbicides when the wind velocity will cause major movement of herbicide spray patterns or when the direction will cause drift toward susceptible crops or ornamentals

4. When using esters, use only low-volatility formulations when temperatures are likely to exceed 70° F; oil-soluble amines are nonvolatile and perform similarly to esters in controlling brush

5. Where feasible use tree injection along boundaries

6. Drift-control formulations and equipment are available for projects that offer prospects of drift damage

Conclusions

Most biological problems in forestry lend themselves, in some way, to solution with herbicides. Insects, diseases, and inadequate allocation of productive capacity to salable species are environmentally linked problems. Fortunately, improvement of crop tree habitat tends to discourage some weeds, diseases, and insects. Inexpensive and selective herbicides permit forest managers to cull stands to discriminate against diseased and infested trees, releasing valuable crop trees at the same time. These uses of herbicides are ecologically sound.

Herbicides can cause great destruction. In the case of some herbicides, as little as 1 lb/acre can kill most living trees in a bulky and complex forest. Such destructive power must not be regarded lightly. On the other hand, the potential for creative use of these materials has provided landowners with an exciting new opportunity for accomplishing their objectives in forestry. The possibilities for damage are generally well documented. However, by optimizing the balance of benefits over hazards, herbicides can be used beneficially to replace many practices of known adverse environmental impact.

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GRAZING LANDS

Introduction

Almost half the total land area of the United States is used for grazing purposes. Weeds and brush infest nearly all these forage lands and are a serious problem on a high percentage of them. Economic losses from weeds on foragelands include low yields of forage and animal products per unit area, livestock poisoning, reduced habitat values for many species of wildlife, reduced groundwater yield, increased costs of managing and producing livestock, and increased frequency of new seeding failures (Klingman, 1970).

Trends toward dominance by weeds can be halted or changed by the judicious use of mechanical or herbicidal control methods, introduction of new forage-plant species, fertilization, and control of the kinds and numbers of grazing animals and their season of use. Some grazing lands do not respond readily to improvement measures because of such factors as climate, native animal life, plant species, low soil productive capacity, or erosion. Nevertheless, many foragelands can be made more productive by present techniques, which often include some form of weed control.

Efforts to correct weed and brush problems in foragelands have been minimal. Almost every year there is an increase in the scope of the problem. Future research undoubtedly will improve control methods; however, we already know enough to be doing far more in this field.

Weed competition is a particularly frequent and serious problem during the establishment of new stands of forage crops from seedings. The slow growth of the forage seedlings provides opportunity for rapidly growing weeds to overtop and severely shade them or to exhaust the moisture supply in the soil before the forage-seedling root system is well developed. The control of weeds often makes the difference between success and failure in such seedings (Klingman, 1970).

Scope of the Weed and Brush Problem.—Brush infests 320 million acres of the almost 1 billion acres of land used for grazing in the continental United States (Sampson and Schultz, 1957). In addition, poisonous and other herbaceous weeds are found in all grazing lands—they are abundant on ranges in poor condition but less so on ranges in good condition.

The estimated loss resulting from brush and weeds in $237,000,000 on rangelands and $396,000,000 on pasture lands. This is based on an estimated loss in yield of forage of about 13 percent in the western half of the United States and 20 percent in the humid Eastern States (LeClerg, 1965).

During 1968, over 9 million acres of grazing land were sprayed with herbicides at a cost of $36.2 million. Of this acreage, about 4.4 million were rangeland and 4.7 million were pasture. Farmers or ranchers used their own equipment to spray only 17 percent of the rangeland but 74 percent of the pasture. Commercial applicators treated the remainder in each case.

The cost of spraying rangeland is higher than the cost for pastures mainly because relatively more brush species on rangelands were sprayed with 2,4,5-T. The less expensive 2,4-D is effective on many pasture weed species and is more commonly used on pastures. Also, the rate of herbicide required to control brush is usually higher than that needed to control herbaceous weeds (USDA, 1972).

Nature of the Problem.—Weed control in pastures and rangelands involves special problems. The forage frequently consists of many plant species, including many species of grasses intermixed with other desirable species such as legumes and browse. The forage species are interspersed with undesirable woody plants and other weeds. Selective elimination of the undesirable species is a prerequisite to upgrading the range vegetation. Subsequently, competition from the desirable vegetation is needed to minimize reinvasion. Herbicides with a sufficiently broad spectrum of efficacy to kill many types of weeds and brush frequently eliminate some of the desirable forage species as well. Also, some weeds are resistant to a weed-control treatment. These resistant species tend to spread when the treatment kills other competitive weeds.

The complexity of the weed-control problem is indicated by a survey conducted in1965 (USDA, 1968). There were 147 weed species listed among the "five most important weeds" on pastures and haylands in the various states responding to the survey and 105 species listed on rangelands. These weeds include grasses and broadleaf species that were annuals, perennials, and woody plants. Control procedures for these various types are quite different.

The invasion of weeds and brush, and conversely their control, results from the interplay of myriad environment, soil, plant, animal, and climatic variables. Thus it is important to integrate the chemical, cultural, and management systems of weed control with the management practices required to produce high-quality forage for animal consumption (Klingman, 1970).

Weeds infest grazing lands across many climatic conditions ranging from arid to humid, on soils varying from sand to clay, and in vegetative types from improved pastures to resident vegetation. The selective control of weeds must be adapted to the situation and site where weeds are normally a problem. Advantage can be taken of agronomic practices favorable to the vigorous growth of grasses and legumes in pastures. The competition of vigorous forage species contributes to and helps hold any gains made by the control method. The control method may need only to "tip the balance" in favor of forage crops.

The only purpose and the primary impact of weed control is to change the vegetative composition of a site. Thus weed control always has an ecological impact. The objective is to change vegetative composition to a stage desired by man, which often is a subclimax vegetational type. The indirect effects of weed control are very important. Most of these are beneficial in some situations to wildlife, domestic animals, birds, and man. It is also true that many indirect effects under some conditions may be disadvantageous to one or more species. The direct harmful effect is usually minimal. There is almost no correlation between the direct phytotoxicity of herbicides and animal toxicity when all modern organic herbicides are considered.

Brush Control on Rangelands.—Brush removal can improve grazing on an estimated 240 million acres (Armour's Analysis, 1952). Examples of important brush problems include 70 million acres of mesquite (*Prosopis* spp.) (Parker and Martin, 1952), 76 million acres of juniper (*Juniperus* spp.) (Anon., 1951), and 96 million acres of sagebrush (*Artemisia* spp.) (Pechanec *et al.*, 1965). More than 80 percent of grazing land in Texas alone is infested to some extent with brush (Smith and Rechenthin, 1964).

Spreading of Native Plants to Become Weeds.—Originally, native woody plants were a lesser component of the climax vegetation of North American grazing lands. Some authorities believe that in early times repeated fires kept grasslands relatively free of woody plants (Humphrey, 1958). During those times, less intensive grazing of forage permitted enough grass to accumulate to serve as fuel for the intense fires that killed young trees and shrubs. After settlement of the frontier, intensive grazing steadily reduced the available fuel.

More recently, man has largely excluded fire from rangelands. The deterioration of ranges has resulted in accelerated invasion by undesirable brush. For example, mesquite dominated only 5 percent of a southern New Mexico range before 1858, but had taken over 50 percent of the range by 1963; tarbush occupied less than 1 percent of that area in 1858 and 9 percent in 1963 (Buffington and Herbel, 1965). Today, the brush invasion of grazing lands annually exceeds the acreage on which control measures are applied (Day *et al.*, 1968).

Management Practices That Should Accompany Brush Control.—Sound management principles are essential to the use of control methods on brush-infested rangeland. Relatively little improvement can be made, however, without eliminating the brush by spraying, burning, grubbing, rootplowing, cabling, or some other method. Each method has specific advantages and many have certain limitations. Once established, woody plants like mesquite, juniper, oak, and sagebrush cannot be eliminated by good grazing practices alone. Measures must be taken to convert the brush to more productive types of vegetation. Brush control must be combined with other practices favorable to forage production that will alter the direction of successional trends (Day *et al.*, 1968).

Domestic livestock, game, rodents, and other animals contribute to range weed problems by creating opportunities for the establishment of weed seedlings and spreading seed or vegetative propagules. Grazing alters the botanical composition of range vegetation because of differences among species in palatability and ability to withstand grazing. The range animal, for example, first grazes the most palatable forage plants on the more accessible parts of the range. As plants are progressively weakened by close and frequent cropping, the less palatable plants (weeds) grow unhindered. Severe grazing can kill forage plants. Persistent heavy grazing increases the proportion of short grasses at the expense of more productive taller grasses. Vigorous tall grasses offer resistance to invasion by range weeds (e.g., mesquite) whose seedlings require intense sunlight. Good grazing management usually results in more desirable species composition, vigorous individual forage plants, and ample seed production. Usually, perennial grasses on arid rangelands thrive under stocking rates that remove about 50 percent of the current year's herbage. Range seeding and related cultural practices can also be used to directly increase the density of the forage stand (Day *et al.*, 1968).

Seedings often fail to become established under the adverse environmental conditions of arid and semiarid rangelands. Brush control is therefore of the utmost importance when invasion is just beginning and before the grass has been depleted. Brush-infested lands that still have a good stand of grass as understory require a herbicidal or mechanical brush-control method that does not destroy existing grasses. Conversely, mechanical methods alone may be most effective if there is a dense stand of brush with few or no desirable grasses, if the soil and climate are adequate to support grass production, and if there is good probability of grass establishment after brush removal (Klingman, 1970).

Some measure of weed control may be obtained by selection of the kind of animals and the timing of livestock grazing on a range. Goats, for example, browse on woody plants more heavily than do cattle or horses. Sheep sometimes graze and thus control herbaceous weeds. However, livestock may also spread weeds from one range to another. The fruits of many range weeds are relished by livestock, and their seeds are spread to uninfested areas when they pass through the digestive tract in a viable condition. For example, in the case of livestock feeding on mesquite beans (*Prosopis* spp.) or cactus fruits (*Opuntia* spp.), it takes a bout a week for the digestive tract to clear; allowance should be made for this before moving the cattle to an uninfested range.

Some form of deferred or rotational grazing may be necessary to restore vigorous forage stands on overgrazed sites near livestock water and salt. Appropriate intervals between grazing periods allow the forage plants to regain vigor and set seed. Heavier stocking for only a part of the year spreads grazing of forage plants on the more accessible sites. Adequate distribution of watering facilities, judicious placement of salt, and other methods of spreading the grazing pressure over the entire range reduce the danger of injury to forage plants and thus forestall weed and brush invasion (Klingman, 1970).

The control of brush may require modification of currently practiced management systems. Forage production for the first 2 to 4 years following successful brush control may be as much as 400 percent greater than before. This high production usually declines somewhat in subsequent years. For example, the actual long-time improvement in forage production after brush control may be only 30 percent on sandsage and mesquite rangelands and about 100 percent on shinnery oak (*Quercus harvardii*) rangelands. Nevertheless, profits per acre on sandsage rangelands may be doubled over a 20-year period by one successful brush-control operation. The increase in profits is even higher when shinnery oak is controlled (McIlvain, 1966).

In special situations, control of only a portion of the brush by herbicide treatments, rather than the eradication or control of a high percentage, provides better long-time management alternatives. Partial control of shinnery oak brush increases forage production from 50 to 100 percent and usually gives a more manageable grass stand. On the light sandy soil habitat characteristic of shinnery oak the remaining oak plants also retard wind erosion during severe droughts. If only a part of the area is treated, one should avoid concentration of livestock on the controlled acreage to the point of causing overuse. Grazing of the controlled area should be deferred for a growing season or more following treatment to allow the reestablishment of forage plants.

In addition to increased grass production, brush control also results in the following:

1. Increased ease and reduced cost of caring for livestock
2. Increased number of offspring
3. Reduced screw worm and other parasite damage
4. Tamer livestock
5. Fewer breeding males required
6. Improved habitat for many species of wildlife
7. More groundwater production over a longer period of time (Klingman, 1970)

Methods of Brush Control

Methods used for brush control vary greatly in cost and effectiveness. Because the potential income from grazing lands with a brush problem is low, costs and benefits of the alternative methods should be considered more carefully than may be necessary for more valuable lands. Because of the large areas involved, brush eradication on rangeland is rarely the objective; emphasis is usually placed on control or regulation of a problem species. A major difficulty in achieving control is the efficient reproduction of many woody species. The capacity to regenerate asexually is common to such problem species as mesquite, oak, elm, and cactus (Klingman, 1970).

Herbicidal Control

Foliage Sprays.—Herbicides such as 2,4-D, 2,4,5-T, Silvex, and benzoic acids control many species of brush. Picloram also shows exceptional promise on many brush species. A combination of 2,4-D and 2,4,5-T is sometimes used to control mixed brush because of the varying susceptibility of species, but 2,4-D and 2,4,5-T do not act synergistically, and their effects are not fully additive.

The choice of a herbicide is determined by cost, effectiveness, and safety. The relative costs of herbicides are quite different. The least expensive is 2,4-D, and it is used where it is effective. The cost of 2,4,5-T is about 2.5 times that of 2,4-D, and the former is used only when 2,4-D is inadequate. Similarily, dicamba is about six times as expensive as 2,4-D and picloram about 18 times. Where possible and efficient, mixtures of more expensive herbicides with less expensive ones are the rule. The expensive ones are used only when required for effective control.

Brush plants are most susceptible to foliage applications of herbicides after leaves have reached full size, the flush of new leaf development has stopped, terminal growth has slowed, and before a thick leaf cuticle is produced. This also coincides with the time that transport of photosynthate to the roots peaks and when carbohydrate reserves stored in the root system and stem bases are at the minimum level (Tschirley and Hull, 1959).

Plants are generally most sensitive to foliage sprays of growth-regulator herbicides under optimum growing conditions. In some dry years herbicide treatments should not be made at all, since plants under moisture stress do not readily translocate phenoxy herbicides. In Oregon, for example, poor control resulted when the soil moisture was depleted before rabbitbrush reached a susceptible stage of growth (Hyder *et al.*, 1962). Studies in New Mexico showed that there was a 39-percent increase in the control of mesquite for each additional inch of rainfall during the October-to-May period preceding treatment.

Heavy applications of Silvex proved effective in controlling pricklypear (*Opuntia polyacantha*) in Wyoming, particularly when spraying was preceded by running over the weeds with a cultipacker (Thatcher *et al.*, 1964). The cultipacker causes abrasions that apparently facilitate absorption. The roller may also orient the pads in a horizontal position, which improves coverage.

Brush control on range lands does not last indefinitely after treatment. Many species resprout from the base of the stem or roots after the tops are killed by herbicides. The rate of recovery of the brush cover, by sprouting, depends on species and environment. Treated areas also become reinfested by seedlings arising from seeds present in the soil or brought in from nearby areas (Fisher *et al.*, 1959). In any event, re-treatment is necessary on sites where woody plants are well adapted. It is important that the ranch managers plan for a long-range followup control program on their grazing units.

To achieve adequate initial control of many woody plants, two or more herbicidal treatments are necessary in consecutive or alternate years (Elwell *et al.*, 1954). Adequate control usually lasts 7 to 15 years. Re-treatment of more susceptible brush species or species with weak regenerative potential may be required at less frequent intervals.

The amounts of herbicide needed to give adequate control varies among species. Effective rates are 0.33 to 0.5 lb/acre of 2,4,5-T for velvet or honey mesquite; 2 lb/acre of 2,4-D for big sagebrush (*Artemisia tridentata*); and 2 lb/acre of 2,4,5-T applied for 2 or more years for post and blackjack oak (*Quercus stellata* and *Q. marilandica*). Higher rates are rarely more effective and may cause foliage and branches to die so quickly that the herbicides are not translocated to the vital sites (Klingman, 1970).

Fixed-wing or helicopter aircraft are commonly used to spray herbicides over large areas. Foliage sprays can also be applied with ground equipment, but the terrain as well as the size and density of the brush often preclude this.

Since minimal volumes and rates of herbicide are used in spraying for brush control, efficient spray distribution is critical. Poor results can often be traced to poor spray distribution and coverage. The factors influencing distribution include swath width, height of spray release, nozzle placement and orientation, and physical characteristics of the spray. In applying phenoxy herbicides to mesquite, it has been established that about 70 drops per square inch are needed for minimum coverage (Behrens, 1957). Finely atomized spray drops may drift from the target area or evaporate before reaching foliage. Spray-droplet size should therefore be large enough to minimize drift hazards but sufficiently uniform to provide good foliage coverage.

Soil Applications.—Variability in seasonal susceptibility is less of a problem with herbicides absorbed from the soil than it is with foliage-applied herbicides. However, the rates or treatment are often higher, and selectivity may be lower than that obtained with foliage sprays. Monuron, fenuron, picloram, and other herbicides are applied as granules in broadcast treatments or around the base of individual plants. Applications should be made when there is a reasonable chance that rainfall will carry the herbicide into the soil. If herbicides are applied when rainfall is light, losses through photodecomposition and volatilization may be excessive.

Individual stem treatments of brush with herbicides are usually limited to sparse stands of single-stem trees or to small areas of range land. The three categories of stem or basal treatment are basal stem, frill or tree injection, and cut stump.

In basal-stem treatments either diesel oil or kerosene, alone or fortified with a herbicide, is sprayed on the base of the tree stem so that it thoroughly wets the bark and runs down the stem to wet the crown at ground level. This method is particularly effective on hardwood trees, during winter or summer, where the trunk diameter is less than 6 inches and the bark is not too thick. Applications of phenoxy herbicides in a water carrier are not effective.

Most species can be controlled with frill and tree-injection techniques. In the frill method diluted or undiluted herbicides are introduced into cuts made around a tree stem with an ax or some other sharpened tool. Horizontal cuts through the bark should be made as close to the ground as possible. Tools for tree injection have a hole in a chisel point through which herbicide is injected after the chisel is driven into the stem. Depending on plant size and species susceptibility, injections must be made at intervals of from 1 to 3 inches around the stem. Treatments are effective during any season.

The cut-stump method consists of treating the cut surfaces of a recently cut stump. Ammonium sulfamate crystals, herbicides in diesel oil, or water-soluble herbicides in water are applied to the cut surface. The method is effective with most sprouting species. Applying the herbicide to the stump soon after cutting improves the likelihood of absorption before sprouting can occur. Control is most effective if trees are cut close to the ground since the distance the herbicide must travel to the sprouting zone is reduced.

Mechanical and Manual Methods.—The choice between manual methods (e.g., cutting and grubbing) or mechanical equipment to remove brush depends on the size of the woody plants, whether the species have sprouting or nonsprouting characteristics, soil condition, and type of terrain. Mechanical methods have been used to control mixed stands of brush and species that occur in almost pure stands. Various techniques and types of equipment have been developed for different situations.

Manual Methods.—It is best to use manual methods of cutting or grubbing during early brush invasion and before the grass stand becomes greatly reduced. Grubbing or cutting sparse stands of small shrubs (up to 36 inches canopy diameter) by hand is an economical method of control (Herbel *et al.*, 1958). To kill a sprouting species, the root must be severed below the budding zone. With large trees and multiple-stemmed plants the cost is usually prohibitive. After cutting, sprouting species can be advantageously treated with herbicides to prevent sprouting.

Mechanical Methods.—The mechanical methods of rangeland brush control include cabling or chaining, bulldozing, rootplowing, disking.

Cabling or chaining is a process of uprooting trees by pulling a 300- to 500-foot length of anchor chain or heavy cable looped between two large tractors traveling in the same direction. This method is most effective in controlling even-aged, mature, nonsprouting species such as one-seed and Utah juniper. It is less successful against sprouting species such as mesquite and against stands of brush that include both small and mature plants (Klingman, 1970).

Small shrubs or trees are not severely damaged by this method. Medium-sized trees or shrubs may be only partially uprooted. Stands containing a large number of small- or medium-sized trees require followup work by bulldozing or by hand. The method is not effective if the terrain is too steep or has gullies and exposed rocks. Tractors should maintain the highest possible speed.

Cabling or chaining is most successful on areas with a light soil and fairly level topography supporting plants of 3 inches or more in diameter. Small plants bend under the chain or cable and snap back without appreciable damage.

Bulldozing is effective against medium-sized trees of some basal sprouting species and sparse stands of any species since it pushes or pulls the plants out of the soil. Small trees and shrubs are often overlooked and may not be removed by this method. Large trees are difficult to uproot. One problem with bulldozing is that much soil is torn up, leaving large pits.

Bulldozer blades may be fitted with a projection, sometimes called a stinger, which is pushed under the tree crown to ensure uprooting of the bud zone. Experienced operators can lift and push over a tree in one smooth operation. Another equipment modification is a blade that can be both tilted and angled. Experienced operators can cause far less soil disturbance with this type of blade than with a normal bulldozer blade. Bulldozing is difficult on steep, rocky land.

In Arizona the cost of bulldozing an acre with 100 predominantly small juniper trees was $6, and the cost for the same number of larger trees was $9. Cost per tree decreases as density increases because of the shorter travel time between trees. In a hardwood-pine area bulldozing costs were $11 per acre for a tree density of 427 per acre if 90 percent of the trees were 6 inches or less in diameter at breast height. Costs may exceed $20 per acre for larger trees. Followup treatment is required because small plants are missed and resprouts and seedlings soon appear.

Rootplowing with a track-type tractor and a horizontal blade cuts off brush below the ground surface. Rootplowing is limited to deep soils that are relatively free from rocks and obstructions. Fins are welded to the top of the back of the blade to push roots out of the ground and reduce the possibility of their rerooting. Rootplowing generally kills most of the brush that the blade strikes below the budding zone of plants and also kills almost all the grass in the area.

Because areas that are rootplowed must be seeded, the operation should be conducted only in areas favorable to the establishment of the forage seeding. Rootplowing and seeding are expensive operations. The cost-to-benefit ratio is generally favorable when a good grass stand is established and unfavorable when seeding is unsuccessful (Boykin, 1960). Because of the high percentage of control obtained, rootplowing is effective where there is no seed source of the woody plants either in the soil or in nearby areas. It is often difficult to establish new seedings on arid and semiarid range lands where brush is a problem.

Disking for brush control is done with a large disk plow, or tandem disk, which plows up much of the brush. The method is limited to small, shallow-rooted plants such as creosotebush, sagebrush, and tarbush. Soils must be plowable and should contain few desirable grasses since disking destroys most of the grass present. Disked areas must be seeded with desirable grasses. Limitations are generally the same for disking as for rootplowing (Klingman, 1970).

Burning is the oldest brush-control method in use. Prescribed burning may be one of the most useful but more hazardous brush-control practices. The results of burning vary greatly depending on the susceptibility of the species to fire and on the amount of fuel accumulation from the associated forage species. The time of year and moisture relationships are also important. Because of these variations and the hazards to other resources, the value of burning as a brush-control measure is controversial (Lillie *et al.*, 1964; Jones and Laude, 1960).

If burning is employed, consideration must be given to the direct effects of fire on forage species and the tendency for livestock and other animals to concentrate in recently burned areas. Forage species vary in their susceptibility to fire, and the season of greatest susceptibility for the undesirable plants may or may not coincide with that of the forage species. Heavy grazing, coupled with frequent burning, will eliminate the better forage plants.

Burning at the proper season—with proper moisture conditions, appropriate grazing management, and adequate precautions—effectively controls several kinds of undesirable range shrubs. Big sagebrush is an example of a species that does not sprout strongly after burning (Pechanec *et al.*, 1965; Blaisdell, 1953). Fire gives a very limited degree of control, however, of a number of shrubs and trees—such as velvet mesquite (*Prosopis juliflora* var. *velutina*) (Cable, 1961), the oaks (Martin and Crosby, 1955), several species of the chaparral complex, and alligator juniper—since they resprout vigorously at or near the ground. Under certain conditions, however, as in the case of young velvet mesquite plants in southern Arizona and chaparral in California, burning may still be useful as a method of control. After burning, seeding is commonly done in the ashes. Sprouts and seedling brush and weeds should be sprayed the year after burning. The spraying of older brush is less effective.

Burning is no cure-all for the range-brush problem, nor is it necessarily cheaper than other methods. Provision must be made to ensure that the fires do not get out of control. This requires adequate preparation, trained manpower, fire-control equipment, prearranged fire breaks, and judgment as to when burning should be undertaken and when and where it can be stopped. The use of desiccating herbicides to permit more latitude in selecting the time and place of burning is under investigation but is not a widely recommended practice. The cost of burning includes not only the cost of fire lines and other safety precautions but also the loss of one or more forage crops that are necessarily accumulated as fuel to carry the fire. However, burning does offer a degree of control for a number of species wherever it can be properly integrated into a comprehensive, long-range vegetation-management program.

In areas where smoke pollution is a serious problem the use of fire for brush control would likely be considered unacceptable by the public. Furthermore, burning bares the soil, which in turn increases the hazard of wind and water erosion and the consequent pollution of streams and the air with soil particles.

Biological Control and Selective Grazing Methods.—Since the inception of biological control of lantana in Hawaii in 1902, steady progress has been made. Striking successes have been obtained in Australia with prickly pear, in California with St. Johnswort, in Fiji with curse, and in Hawaii with pamakani (Day *et al.*, 1968).

Successes in biological weed control suggest that perennials in noncultivated environments are better adapted to biological control than are short-lived species in cultivated situations.

Because the ultimate geographic distribution of an introduced biotic agent is not usually controllable, all conflicting interests concerning the weed itself should be resolved before an introduction is made. Conflicts of interest arise because some weed species in one situation may be considered to be valuable plants in others (Day *et al.*, 1968).

Biological control of weeds is highly useful and promising on certain individual species. Nevertheless, this method can be used effectively on only a small percentage of economically important weeds, if only because of the conflicts of interest that exist. The other weed species must be controlled by other methods.

Selective grazing by sheep or goats is effective in controlling some species of brush in small areas. The animals select the more palatable plants or portions of the plants and are particularly effective in controlling seedlings and young sprouts. Therefore cutting or otherwise removing the tops of larger trees and shrubs precedes this practice. Close, continuous grazing is necessary to suppress and kill brush. Overgrazing, especially at the wrong times of the year, can be more detrimental to desirable forage species than to the brush species being controlled (Johnston and Peake, 1960). Expenses for the necessary fences, water, death losses, and management of animals can prove exorbitant.

Methods of Herbaceous Weed Control

Herbaceous weeds are found in all rangelands. Their harmful effects vary with the range conditions: good ranges usually have few herbaceous weeds, and poor ranges have many. Loss of forage from herbaceous weeds on rangelands is often less spectacularly apparent than from dense stands of brush; nevertheless, such losses are large.

Grasses are a most important group of herbaceous weeds, and they dominate vast areas of rangelands throughout the world. For example, medusahead (*Taeniatherum asperum*) is spreading in California, Oregon, Washington, Idaho, and Nevada. It is invading stands of forage plants as well as the downy brome (*Bromus tectorum*) and other weed species found on millions of acres of range lands. Except for a short time in the spring, this weed is unpalatable. Because of its low palatability, it accumulates and thus creates a fire hazard. Dead litter also tends to build up and inhibit the early growth of seedlings of planted species.

Downy brome differs from medusahead in that it serves as the main forage species on millions of acres of western range. It is productive and palatable in the spring. However, this annual is undesirable on many ranges in that well-adapted perennial grasses (or other perennial plants) give a more reliable and higher production of forage, especially in adverse years. As downy brome matures, its palatability decreases, and its usefulness as forage declines (Klingman, 1970). Furthermore, the dead plants are a serious fire hazard.

The control of downy brome and medusahead often requires the seeding of perennial grasses combined with grazing-management practices that favor the desirable forage species. Otherwise, any management will yield little except downy brome and medusahead. After the initial establishment of perennial grass seedlings, selective herbicide treatments should be applied to suppress the weeds and thus enhance the rapid development of the perennial grass plants to a level of vigor and basal density that maintains suppression of the weedy annual grasses (Torrell *et al.*, 1961).

That at least partial control of two successive crops of medusahead is required for a successful seeding operation illustrates an important principle related to annual weed control. Regardless of the number of plants per unit area—be it 10 or 1000—their control is essentially a matter of percentages, and high populations are best reduced by successive control measures (Torrell, 1966). For example, in southwestern Idaho medusahead populations range from 250 to over 1000 plants per square foot, with mean values of 325 to 400 plants per square foot. Initially, there may have been as many as 14,000 seeds per square foot. A controlled fire before seed shattering will destroy much seed and reduce the next year's medusahead population 85 to 90 percent below that of unburned areas. Therefore there will be about 35 plants per square foot on the burned site and about 350 on a similar area on the unburned site. Dalapon applied at a rate of 2 lb/acre will kill 98 percent of both populations in the spring a year after burning. The surviving population on the burned site will be some 0.7 plant per square foot versus about seven plants on the unburned site. Practically, this may represent the difference between the success and failure of a new seeding of perennial grass.

Under climatic conditions like those found in parts of California and Nevada, 1 year of tillage in April will give weed control adequate for the establishment of legumes or forage grasses, especially if seeding is accompanied by other weed-control treatments and if annual forage species are seeded (Kay and McKell, 1963).

Control procedures in new seedings would be greatly simplified if there were a truly selective herbicide that would kill the annual weed species and leave the seeded species uninjured. The similarity in physiological and environmental requirements of seedlings of annual and perennial grasses makes such selective control of weed grasses one of the most persistently difficult problems in range improvement. The potentialities for such a herbicide are best illustrated by siduron, which selectively controls the seedlings of crabgrass (*Digitaria* spp.), foxtail (*Setaria* spp.), downy brome, medusahead, and many others without injuring the seedlings of bluegrass (*Poa* spp.), crested wheatgrass (*Agropyron desertorum*), and fescue (*Festuca* spp.). For siduron to be effective, moisture must be available soon after treatment. This limits the usefulness of this herbicide for range seedings.

Several of the wheatgrasses (*Agropyron* spp.) are suitable for seeding in ranges infested with downy brome and medusahead. Mature plants of the wheatgrasses are strongly competitive, but not the seedlings. The use of selective herbicides releases wheatgrass plants from the intense competition of weed grasses.

Paraquat has proved effective in weed-control experiments in Nevada and northeastern California in a program of no-tillage spring seeding of perennial grasses. Paraquat plus a surfactant effectively controls downy brome seedlings and is almost immediately adsorbed by the soil and plant residues; this permits the seeding of perennial grasses immediately after spraying. When added to paraquat, 2,4-D controls the broadleaf weeds that are often associated with downy brome. Paraquat must be applied in the spring, when moisture is often available for only a short time, leaving a short period for seeding operations. Stands of perennial grasses must be established early so that these forage plants are large enough by summer to stand the drought and heat. In years of extreme drought, the chances of successful seeding are almost nil despite the degree of weed control that is obtained. Planting the seed in furrows improves the microenvironment and enhances the probability of perennial grass establishment.

Herbicides active in the soil, such as atrazine, effectively control annual grasses but are toxic to the seedlings of perennial grasses. To achieve selectivity between the weed and the seeded species, it is necessary to use methods that are based on timing, placement, or a combination of both. A chemical fallow technique in which atrazine is applied in the fall of one year and perennial grasses seeded the next has been effective over 10 years of experimentation (Eckert and Evans, 1967). Atrazine is nearly always dissipated from the soil in the intervening year. Weed control during that year eliminates seed production and conserves nitrogen and soil moisture. This technique reduces annual grasses markedly during the seeding year but sometimes increases broadleaf weeds. Under such conditions, good stands of crested and intermediate wheatgrasses have been obtained by planting the seed in furrows in the fall and spraying broadleaf weeds with 2,4-D the following spring.

Broadleaf Herbaceous Weeds.—Broadleaf herbaceous weeds are serious problems in rangelands since many are unpalatable or have spines or thorns. Because livestock avoid such weeds, unless other forage is lacking, broadleaf weeds tend to increase on improperly grazed ranges. Furthermore, they compete directly with desirable forage species for moisture and nutrients, decrease the amount of forage produced, and inhibit the establishment of forage seedlings (Day *et al.*, 1968).

The control of broadleaf herbaceous weeds is complicated by the fact that individual species often occur in scattered stands and frequently on terrain that is not easily accessible for direct control measures. Some species, such as the low larkspurs (*Delphinium* spp.), mule-ears (*Wyethia* spp.), and lupines (*Lupinus* spp.), occur in stands of sufficient density and area to justify overall applications of herbicides.

Many species, notably the larkspurs and deathcamas (*Zigadenus* spp.), become more resistant to phenoxy herbicides at later growth stages. The time of treatment is therefore critical. In addition, plants of such species as the tall larkspurs begin growth as snowbanks recede. This results in many growth stages among closely associated plants of the same species. Under these conditions, plants may range from susceptible to resistant, and therefore re-treatment will be necessary and adequate control costly.

The extensive root systems of some perennial herbaceous weeds, as exemplified by Canada thistle (*Cirsium arvense*), leafy spurge (*Euphorbia esula*), hoary cress (*Cardaria draba*), and whorled milkweed (*Asclepias verticillata*), and the variable effectiveness of phenoxy herbicides on such plants make repeated treatments necessary. Despite the need for repeated annual treatments, phenoxy herbicides are used alone and in combination with improved grazing management, cultivation, and reseeding. Reasonable control can be achieved in this way, but near eradication from a site requires prolonged treatment. In a 6-year study in the Gulf Coast area of Texas, the application of 2,4-D (1 lb/acre) in March of each year resulted in an average increase in forage production from 2400 to 5300 lb/acre. The annual cost for the operation was $2 per acre (Hoffman and Ragsdale, 1964).

Poisonous Weeds.—About half the perennial broadleaf herbaceous range plants presently recognized as weeds are poisonous. Examples of locally abundant poisonous species in climax vegetation are tall larkspur, greasewood, chokecherry, and certain oaks. Many poisonous plants increase in density on misused rangelands because they are not grazed when palatable forage plants are available. There are exceptions, however, such as tall larkspurs (*Delphinium* spp.) and locoweeds (*Astragalus* spp.), which may be habit-forming to livestock (Day *et al.*, 1968).

Poisonous plants are found on nearly all rangelands in the Western United States. Whether they present a problem on range depends on a number of factors. The toxicity of poisonous plants varies with the species and with its stage of growth. Sneezeweeds (*Helinium* spp.) are mildly poisonous; animals may become ill but seldom die if removed from the infested area when symptoms appear. Timber milkvetch (*Astragalus miser*) is so toxic that once cattle exhibit symptoms, they seldom recover; it is, however, apparently relished by cattle and sheep. Tall larkspurs are most toxic during early growth stages. Halogeton (*Halogeton glomeratus*) becomes more toxic with age. Jimsonweed (*Datura* spp.) is very unpalatable and seldom eaten unless animals are starving.

Sparse infestations of poisonous plants are seldom troublesome. Heavy stands of even mildly toxic plants constitute a hazard to livestock. Even small areas of dense infestations of highly toxic species may remove large areas of grazing land from profitable production.

Proper grazing management permits avoidance of poisoning by some species. The life cycle of a poisonous plant can determine whether and when it is a problem on a range. Low larkspurs and deathcamas are problems on ranges grazed very early in the year because they are among the earliest green plants available to livestock. On similar ranges that are grazed later in the season, when forage plants are larger, the animals seldom eat the poisonous species. Still later in the season both poisonous plants have completed their life cycles and disappeared from the range. Tall larkspurs, however, may be at their maximum toxicity during the grazing season.

Poisonous plants are not equally poisonous to all classes of livestock. Tall larkspurs and timber milkvetch are far more toxic to cattle than to sheep. Conversely, only a few cattle losses are definitely known to be due to halogeton, whereas thousands of sheep losses can be attributed to the plant.

Poisoning by weeds causes heavy losses of animals and is a most persistent problem of the range livestock producer. Estimates based on a large number of reports indicate about 3 to 5 percent deaths on tall larkspur-infested range lands. Deaths in some years exceed 15 percent.

Where good range management or other biological control methods do not reduce poisonous weed populations to nonhazardous levels, herbicide treatments may be necessary. Properly timed applications of specific phenoxy herbicides control many poisonous weeds. Repeated annual treatments are required for many perennial species and for annuals and biennials if there is a residual seed supply. The benzoic acids and picloram show special promise against some poisonous weeds.

On sites where herbicides are used for control, judicious grazing management is essential to increase desirable vegetation both in vigor and number of plants, thus reducing the possibility of reinfestation. If an area does not contain sufficient palatable species for natural revegetation, it should be seeded. Proper herbicide treatments after seeding will reduce weed competition and increase the probability of successful seeding and control even on marginal sites. This fact has been demonstrated many times in salt-shrub desert vegetation when halogeton or Russian thistle were controlled in a seeding of crested wheatgrass (Haas *et al.*, 1962).

Brush and Weed Control on Pastures

Every pound of herbaceous weeds grown in pastures reduces the production of desirable forage plants by about an equal amount. Reduction in forage attributable to weeds varies and depends on moisture conditions and the weed and pasture species involved. If legumes are established in the space occupied by weeds, the production of forage will be proportionately greater because of the legume's vigorous growth habit and ability to fix nitrogen (Klingman and McCarty, 1958).

Principles of Pasture Management.—Any practice fostering the development of a thick sod and vigorous growth of permanent pasture species will in time reduce the density of many weed species. Grasses and legumes in pastures vary widely in vigor and density. The vegetation on most permanent pastures of the humid region consists of volunteer grasses and weeds. The forage-weed balance is extremely variable, and in areas with naturally nonacid soils, common white clover (*Trifolium repens*) will usually volunteer.

Liming and fertilization are particularly effective in reducing the weed component over a period of time. In Connecticut, applications of nitrogen, phosphorus, and potassium on a sparse stand of Colonial bentgrass (*Agrostis tenuis*) resulted in a shift to denser bluegrass sod and a consequent reduction in weed growth. Some weed species, however, are favored by fertilization. Examples are chickweed (*Stellaria media*) and curly dock (*Rumex crispus*), which are severe problems only on fertile soils.

Weed-control measures in pastures should foster a high production of nutritious and palatable forage. Weeds can now be controlled by herbicides alone and in combination with other management procedures in pastures more effectively and more efficiently than ever before. In pasture-forage production, all beneficial practices must be integrated into the management system to achieve highest efficiency.

Brush- and Weed-Control Methods.—The general principles and techniques used to control brush and weeds on rangelands also apply to pastures. In general, pastures are more intensively managed and have a higher production capacity. There is, therefore, more flexibility in the choice of possible methods of control on pastures than on rangelands. The potential for a greater increase in forage production may permit the choice of more expensive methods. Moreover, fertilization and liming are more important in weed and brush control on pastures than on arid rangelands.

A large part of the land pastured in the United States is cut-over forest land. Here, without constant control of sprouts and seedlings, the land will gradually revert to timber and shrub species. The major woody plants that must be kept under control include oak (*Quercus* spp.), hickory (*Carya* spp.), cedar (*Juniperus* spp.), pine (*Pinus* spp.), poplar (*Populus* spp.), maple (*Acer* spp.), sweetgum (*Liquidambar* spp.), holly (*Ilex* spp.), basswood (*Tilia* spp.), persimmon (*Diospyros* spp.), sassafras (*Sassafras* spp.), buckbrush (*Symphoricarpos* spp.), rose (*Rosa* spp.), elder (*Sambucus* spp.), hazel (*Hamamelis* spp.), elm (*Ulmus* spp.), and blackberry (*Rubus* spp.).

The potential of phenoxy herbicides for controlling weeds in pastures, alone and in combination with other agronomic practices, has been demonstrated in studies conducted at several locations in the humid and semihumid areas of the United States. These herbicides, including 2,4-D, 2,4,5-T, (4-chloro-*o*-tolyloxy)acetic acid (MCPA), Silvex, and 4-(2,4-dichlorophenoxy)butyric acid (2,4-DB), alone or in combinations, control a wide spectrum of broadleaf weeds and brush. Picloram shows particular promise for killing some weed and brush species.

The practice of mowing many annual and biennial weeds in pastures during the bloom stage of growth largely prevents seed production and may eventually eliminate the weed from the pasture (Klingman and McCarty, 1958). The time of mowing is critically important. Prostrate species and those that branch laterally from buds close to the ground cannot be controlled by mowing. Herbicides are more effective on such species. Even then herbicide treatments may be required for several years to exhaust the supply of weed seed in the upper soil stratum.

Plants growing under optimum conditions are usually more susceptible to herbicides than those doing poorly in adverse environments. Moderately high soil moisture and relative humidity with an air temperature in the range of 70° to 80° F appear to be the optimum conditions for phenoxy herbicides to be effective.

Perennial weeds vary greatly in susceptibility to phenoxy compounds, not only between species but between ecotypes within a species. Variable responses to 2,4-D, ranging from resistance to susceptibility, have been found among ecotypes of Canada thistle (*Cirsium arvense*) in Montana (Hodgson, 1964). In Oklahoma perennial ragweed (*Ambrosia psilostachya*) has been readily controlled by 2,4-D at rates as low as 1 lb/acre. Applications of 1 and 2 lb/acre controlled this weed in central Nebraska; but at Lincoln, Nebraska, a stand of perennial ragweed plants was not reduced on pasture plots sprayed annually for 20 years with an ester of 2,4-D at 1 lb/acre (McCarty *et al.*, 1974).

A few perennial species can be controlled by a single herbicide treatment, but usually one or more re-treatments are required. Re-treatments not only improve the control of perennial weeds but remove crops of annual weeds as well. Herbicide use should continue through the years until the weed stand is reduced adequately. Herbicide treatments, combined with proper fertilization and grazing management, should result in the replacement of weeds by forage species (Peters and Stritzke, 1971).

In many pastures a wide spectrum of broadleaf weeds may create control problems. Rotation of kinds of herbicides or repeated treatments within the season may therefore be needed to carry out an effective control program where a mixture of winter-annual, annual, biennial, and perennial weeds exists. For example, treatments may be necessary in early spring for thistle rosettes, many species of the mustard group, dandelions, and the common snowberry. Such treatments may precede the susceptible stage of emergence of such weeds as ironweed (*Veronia baldwini*), hoary vervain (*Verbena stricta*), goldenrod (*Solidago* spp.), aster (*Aster* spp.), and ragweed.

The use of 2,4-D and other phenoxy herbicides may retard the growth of such legumes as white clover and lespedeza (*Lespedeza* spp.). Stands of legumes may be depleted by early spring spraying. Ordinarily, white clover and lespedeza will recover and eventually benefit from the elimination of weeds and the improved management practices accompanying weed control. If white clover is an important component of the pasture vegetation, 2,4-DB should be used since it causes little injury to white or ladino clover and controls many weeds susceptible to 2,4-D.

Combinations of spraying and mowing have been inadequately explored in pasture weed control. In some areas mowing is desirable for reasons other than weed control. It may, for example, encourage more uniform grazing and favor development of the associated legumes.

Selected Data Comparing Different Methods of Weed and Brush Control

In comparing alternative methods of controlling weeds and brush, it should be recognized that the effects resulting from different methods of control are never exactly the same. Therefore in a strict sense the comparisons are not valid. If one method kills all the weed species but one and a second method kills all but one other weed species, the results from control in an area will seldom be the same because of the different characteristics of the species that escaped treatment.

The coincident impacts of different methods on soil, air, water, flora, and fauna are also quite different. The relationships of the impacts on these environmental factors will vary with site. For example, denuding the land by mechanical treatment or burning will be more likely to result in water erosion on steep, erosive soils than on nearly level, stable soils. Selective control by herbicides usually leaves the vegetation in place. Because of the herbicides' selectivity and slowness of action, the species of plants that are not killed increase in size and cover coincident with the slow death of unwanted species, thus providing soil protection.

Each weed situation, site characteristic, and geographic location will also influence the choice of control method. The chances of successfully reseeding after rootplowing are reduced in very arid climates and on steep slopes. Burning on grazing land near metropolitan areas may be unacceptable because of the smoke that pollutes the air. Use of phenoxy herbicides near cotton fields or residential areas may be prohibited, especially when cotton is growing. In many states these herbicides can be used only before cotton is planted and after it is harvested.

Table 1. FORAGE PRODUCTION UNDER SEVERAL COMBINATIONS OF SPRAYING, TILLAGE, AND SEEDING ON BIG SAGEBRUSH RANGE, 1950-1953[1]

Treatment[2]	Forage yield, oven-dry (lb/acre)	Cost of treatment
Plowed and drilled	921	$9.00
Sprayed, disked, and drilled	842	11.35
Sprayed, not seeded	508	3.35
No treatment	137	0

[1] Source: Cornelius and Talbot (1955).

[2] Sprayed with 2,4-D in July 1948; seeding done in fall of 1948.

Table 2. YIELD OF OVEN-DRY FORAGE ON TREATED AND UNTREATED SILVER SAGEBRUSH RANGE, 1951 AND 1953[1]

Treatment[2]	Forage yield, 2-year average (lb/acre)	Estimated cost of treatment
None	60	0
Sprayed with 2,4-D	459	$3.35
Sprayed with 2,4-D and drilled	790	$8.35
Plowed and drilled	882	$9.00

[1] Source: Cornelius and Talbot (1955).

[2] Sprayed with 2,4-D in 1948; seeding done in fall of 1948.

Selected examples comparing the results of different weed-control methods illustrate some of the differences among the methods and reasons why different methods may be chosen under various situations. Much of this information is presented in tables to facilitate comparison.

Eight years of research in the plateau region of northeastern California have shown that seeding and weed control are practical means of quickly restoring productivity and reducing erosion on deteriorated rangelands (see Tables 1 and 2).

Research in California has also shown that ranges with terrain too steep, erodable, or rocky for cultivation can be successfully seeded by spraying the resident annual grasses with paraquat and planting immediately (see Table 3).

The spring following seeding, harding grass plants in the unsprayed plots were mere threads with two or three leaves and 2 to 7 inches high. In plots sprayed with paraquat the plants were robust, had one to six leafy tillers, and were 12 inches high. The plants in unsprayed areas died during the summer, while those in the sprayed plots survived to produce large, mature plants the second year.

Removal of fringed sage in North Dakota by spraying 2,4-D at a rate of 2.5 lb/acre significantly increased yields from all treatments (Lorenz and Rogler, 1962). During a 12-year, eight-treatment crested wheatgrass renovation study, the average yields for sprayed and unsprayed plots were 1461 and 1137 lb/acre, respectively. The average increase in yield for spraying in the 3 years was 57 percent.

In Colorado 13 prominent weed species decreased 40 percent or more after the application of 2,4-D at a rate of 2.2 kg/ha (Hyder, 1971). This resulted in a botanical composition that was grazed more uniformly and completely. Hence, spraying mixed-grass prairie with 2,4-D improved the range

Table 3. PERCENT HARDING GRASS AND SUBCLOVER ESTABLISHMENT ON PLOTS SPRAYED AND SEEDED OCTOBER 25, 1963, IN SONOMA COUNTY[1]

Treatment	Subclover, April 1964 (%)	Harding grass, January 1965 (%)
Check (no spray)	48	0
Paraquat treatment:		
Complete coverage	81	75
11-inch band	80	60
5.5-inch band	74	58
LSD, 0.05 level	14	17

[1] Source: Kay (1966).

condition and increased forage production. Yields of oven-dry forage, averaged for the 3 years, were 580, 710, and 680 kg/ha for untreated plots and for plots sprayed before and after the heading of sandberg bluegrass, respectively. "There are no known alternative ways of making these improvements in a reasonable time" (Hyder, 1971).

"Natural rehabilitation of mule-ear-infested ranges by protection from grazing requires many years and is believed beyond the realm of economic practicality" (Tingey and Cook, 1954). Mule-ear was successfully controlled in Utah with 2,4-D applied at a rate of 2 lb/acre. In one case, 5 years after treatments were made, a series of untreated plots infested with mule-ear yielded 280 lb/acre of desirable forage; where the weed had been eliminated, the yield was 1353 lb/acre. Bunch wheatgrass, Kentucky bluegrass, and needle-and-thread grass increased in direct proportion to the extent of mule-ear control.

Five years after spraying oak-hickory vegetation with 2,4,5-T in Missouri, the total herbage yield was about 4.5 times that on the burned areas and 5.5 times that on the control area (Ehrenreich and Crosby, 1960).

Demonstrations in all parts of Texas have shown that it is nearly impossible to eradicate brush from grazing land. Brush-infested range lands can be restored to high production when the landowner plans and carries out a complete brush- and weed-control program, including maintenance control and improved grazing management (Hoffman, 1970).

From 1965 to 1969 there was mechanical weed and brush control on 2.8 million acres of grazing land in Texas, and chemicals were used on 2.9 million acres. During the last 10 years the acreage under mechanical control remained about the same, and the acreage under chemical control more than doubled (Hoffman, 1970).

Information from the Rio Grande Plain region of Texas and in the post and blackjack oak region of Texas shows that all brush-control methods are economically feasible, with the exception of bulldozing. Bulldozing is not usually used in this area for range improvement except in particular situations (Morrow *et al.*, 1962).

Chemical methods increased net returns for the benefit life of the treatment by $23.62 per acre in the post oak region and by $4.47 per acre in the mixed-brush areas of south Texas. Many brush species of the Rio Grande Plain (south Texas) are not well controlled by 2,4,5-T. Rootplowing and reseeding increased the net return by $35.35 per acre, and chaining increased it by $6.03 per acre (Morrow *et al.*, 1962).

Research in Nebraska has shown mowing to be relatively ineffective on many perennial weeds in pastures but moderately effective in controlling several annual and biennial species (see Table 4). Good control of most troublesome broadleaf weeds results from successive annual applications of 2,4-D at a rate of 1 lb/acre. The total forage consumption increased as the proportion of broadleaf weeds in the material consumed decreased.

Some cost estimates show the difference in return for different practices in a weedy pasture (see Table 5). The advantage of spraying 2,4-D over mowing for weed control in this pasture is obvious. The use of 2,4-D resulted in gains intermediate between the check and improved pastures that were plowed and reseeded. The cash outlay for spraying was relatively low.

Spraying with 2,4-D reduced lanceleaf ragweed populations more than did mowing (Peters and Stritzke, 1971). Four annual sprayings with 2,4-D reduced stands of yarrow by 66 percent; mowing had little effect. Spraying 2,4-D for 3 years nearly eliminated ironweed; mowing for 4 years reduced ironweed by about 50 percent.

High-level fertility plus 2,4-D increased by 1000 lb/acre the consumption of forage by cattle over the high-fertility, no-weed-control treatment; high fertility plus mowing increased consumption by about 200 lb/acre (Peters and Stritzke, 1971). Plowing, fertilizing, and seeding orchardgrass and ladino clover eliminated weeds for 2 years, but in the third year the orchardgrass stand became thin and weeds became numerous. One year's production was lost because the first seeding failed to become established. When all years of the experiment were considered (including the years of no pro-

Table 4. SIX-YEAR AVERAGE OF DRY-MATTER CONSUMPTION UNDER DIFFERENT WEED-CONTROL METHODS IN A DEFERRED AND ROTATIONALLY GRAZED PASTURE NEAR LINCOLN, NEBRASKA[1]

Treatment	Forage consumed (lb/acre)	Percentage of weeds
None	880	41
Mowed[2]	1100	19
Sprayed (2,4-D)[2]	1250	7
Plowed, seeded, and sprayed	2500	4

[1] Source: McCarty and Scifres (1968).

[2] Data from mowed and sprayed plots represent averages of June and July treatment dates. Sprayed plots annually received 1 lb/acre of 2,4-D, isopropyl ester, on the same dates as mowing.

Table 5. ESTIMATED AVERAGE ANNUAL COSTS AND RETURNS PER ACRE FROM VARIOUS SYSTEMS OF PASTURE MANAGEMENT IN NEBRASKA[1]

System	Estimated pounds of beef per acre	Value of beef at $0.20 per pound	Average annual cost	Net return per acre
Rundown native pasture:				
Check	76	$15.20	$7.50	$7.70
Mowed	56	11.20	8.20	3.00
Sprayed (2,4-D)	95	19.00	8.70	10.30
Improved pasture:				
Brome grass	148	23.68	7.50	16.18
WSG mixture	163	26.08	9.20	16.88

[1] Source: Finley *et al.* (1958); estimates projected over a 10-year period.

duction on orchardgrass), the amounts of forage consumed were about equal on the orchardgrass plots and on those receiving high fertility plus 2,4-D.

Picloram killed nearly all the goldenrod plants in a timothy crop (Peters and Lowance, 1969). The 2,4-D and 2,4-DB formulations reduced yields of goldenrod by 75 to 95 percent. Timothy was not noticeably injured by the herbicides, and its yields increased by 0.8 to 1.0 pound for each pound of weeds that failed to grow. There is no other known way of selectively controlling these weeds in this grass crop.

"Increased streamflow has been noted for 3 successive years since a streamside strip within central Arizona watershed was chemically treated to convert chaparral to grass cover. Prior to treatment, the channel was dry several months each year. Since treatment, flow has been continuous at the outlet, and water has been permanently available for wildlife and livestock at several places along the channel" (Anon., 1970, p. 31).

"Winter grazing studies with tame mule deer on sagebrush ranges in central Colorado revealed that deer prefer forbs and grasses over sagebrush. These studies . . . also suggest that careful use of 2,4-D herbicide with fertilizer can improve the vegetative composition of these important areas for deer grazing" (Anon., 1970, p. 16).

As a result of several seasons' use of 2,4-D and 2,4,5-T in southern Michigan, it is generally agreed that use of the herbicides has enabled biologists to do a better job of habitat management than was done in the past (Ruch, 1957). There is an urgent need for economical methods of creating and maintaining openings by controlling unwanted vegetation. Such openings are important to grouse, rabbits, and deer.

Restricting the use of phenoxy herbicides on 62 million acres of all cropland would eventually substantially increase cost to consumers (Fox *et al.*, 1970). The immediate effect would be an increase of $290,000,000 in production costs to farmers. In addition, farmers and their families would have to work 20 million more hours to control the weeds without these herbicides. The farmers would receive no additional income for this extra labor.

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AQUATIC USES

Some form of aquatic vegetation occurs in all streams and bodies of water. It is as essential to the aquatic environment as other plants are to the terrestrial environment. The ecological significance of aquatic vegetation exceeds that of any other forms of aquatic organisms. It provides the basis of the food chain for other forms of aquatic life and is the habitat for much of the aquatic fauna. Essential as they are, excessively large populations or masses of aquatic plants may become highly detrimental to other aquatic organisms and reduce the usefulness of water for many other purposes.

Characteristics and Distribution of Troublesome Aquatic Vegetation

Aquatic vegetation is readily observed in all but the coldest, deepest, or most heavily polluted waters. Even in these waters, close examination usually reveals some type of plant life. The forms of aquatic vegetation range from microscopic plankton to large vascular plants such as cattail (*Typha* spp.) and waterhyacinth [*Eichornia crassipes* (Mart.) Solms]. Under certain environmental conditions and water quality criteria, all forms can create problems in water.

Algae.—Algae are nonvascular plants that range in size from microscopic unicells to macroscopic filaments, sheets, clusters, or tubes. In a few genera, such as *Chara*, the algae may appear to be rooted vascular plants. Algae are almost universally present in water. Many species are quite specific as to the ecological sites they may occupy. Some species prefer hard or alkaline waters, others prefer soft water of low pH. A characteristic common to many algae is their appearance in "blooms" during certain periods. A bloom may consist of a single species or may be due to several species. In some waters the succession of blooms during a given season can be predicted with reasonable accuracy. In irrigation systems it is more typical to observe a single predominant species (usually filamentous) during the entire season.

Vascular Aquatic Plants.—This group consists of a vast array of floating, submersed, emersed, and marginal weeds. Many are useful and desirable species that provide food and habitat for waterfowl, fish, and aquatic insects; some are desirable for their aesthetic value. Certain species are largely undesirable and add little to the total aquatic environment.

Floating Plants.—These plants float individually or in mats on the water surface. They vary in size from the minute duckweed (*Lemma minor* L.) to the large species, such as waterhyacinth and alligatorweed [*Alternanthera philoxeroides* (Mart.) Griseb]. The more troublesome floating plants are of tropical or subtropical origin and are of most concern in the Southern states.

Submersed Plants.—These are rooted plants that grow submersed in water, although they may frequently grow to the water surface. This group includes such species as American pondweed, which have flat leaves that float on the water surface. Typical of submersed plants are the pondweeds (*Potamogeton* spp.), elodea (*Elodea canadensis* Michx.), and watermilfoil (*Myriophyllum* spp.).

Emersed Plants.—Emersed plants are rooted in the soil and rise above the water surface. Because they are usually restricted to shallow water, they are commonly found in most drainage canals and ditches and on the shorelines of streams and lakes. Cattails, bulrush (*Scirpus* spp.), and pickerelweed (*Pontederia* spp.) are common emersed species.

Marginal Plants.—Marginal aquatic plants commonly occur at the margins of lakes and streams. Many of these plant species are also adapted to wet marshy sites. Some of the most important of these weeds are grasses, including johnsongrass [*Sorghum halepense* (L.) Pers.], reed canarygrass (*Phalaris arundinaceae* L.), and paspalum (*Paspalum* spp.). Other common marginal weeds are sedge (*Carex* spp.), smartweed (*Polygonum* spp.), and primrose (*Jussiaea* spp.).

Activities and Resources Affected by Aquatic Vegetation

There is scarcely an activity or resource involving water that is not affected in some way by aquatic vegetation. The biological productivity of water can be maintained only by the presence of aquatic flora. Ideally, the mass of vegetation produced should be adequate to support the various other forms of aquatic life at the optimum level without preventing or limiting the other beneficial uses of water. In many situations, the strata of productivity of aquatic plant life that support specific activities at optimum levels will be in conflict with other uses. A satisfactory solution would be to maintain the vegetative productivity at the highest level tolerated by all or the majority of the various activities and resources affected.

Irrigated Agriculture.—Irrigated agriculture is totally dependent on an adequate supply of water during the growing season. The consequences of any lengthy interruption in delivery of water during this period are disastrous to the farmer who depends on irrigation water. The planning of irrigation districts is such that, when fully developed, water-conveyance structures must operate at full capacity to satisfy the needs of all farmers in the district. Unfortunately, irrigation canals provide ideal sites for the growth of certain algae and vascular weeds, which soon invade these areas. Even small amounts of algae and rooted weeds cause significant losses in the volume of water flow. Heavy infestations can reduce water flow as much as 80 to 90 percent and cause water levels to rise and wash out canal banks. Not only is valuable water lost but flooding occurs in the vicinity of the break while other farmers must do without water until repairs are made. Algae and other aquatic plants also lodge in water outlets, siphons, pumps, sprinklers, trash racks, and other structures, causing lost time, inefficient use of water, and large maintenance expenses.

According to statistics from the agricultural census (USDA, 1959, 1964), there are more than 2 million farm ponds and reservoirs (many used for irrigation), 189,000 miles of drainage ditches, and 173,000 miles of irrigation canals in the United States. A survey of weed problems on irrigation systems in 17 Western states (Timmons, 1960) reported that 63 percent of the 144,000 miles of irrigation canals were infested with aquatic weeds. Also, more than 75 percent of 530,000 acres of canal banks were infested with a variety of weeds. Similar weed problems occur in other areas of the country. In 1965 direct losses to agriculture in the United States caused by aquatic and bank weeds amounted to $52,000,000 (USACE, 1965). The net productive value of lost water alone was estimated at $91,000,000 (USDA, 1965).

Recreation.—The extent to which aquatic vegetation influences or affects recreation has never been determined; whether such a determination is possible is questionable. Most of the streams and natural and artificial water impoundments are multiple-purpose resources. Some of the recreational uses are not compatible. Swimming, waterskiing, and pleasure boating are not entirely suited to waters managed primarily for fishing or waterfowl production. Many observations and experience support contentions that aquatic vegetation is a serious problem affecting recreational uses of water. While aquatic plants are a natural and essential component of the aquatic environment, they can despoil this environment simply by their presence in excessive numbers and in areas where they are undesirable.

Property Values.—There are few recorded or reported instances of property values being affected by aquatic vegetation. Nevertheless, the history of property development adjacent to lakes and streams is ample evidence that aquatic weeds are an important element in determining the value and desirability of such property. Clear weedfree or relatively weedfree lakes and streams have always had a high priority for the location of waterfront homes and vacation facilities. Serious infestation by aquatic weeds subsequent to the development of such areas drastically reduces the desirability and value of waterfront property. Holm *et al.* (1969) cite an example of the effect of aquatic vegetation on the operation and value of a resort motel and marina constructed on what was once one of Florida's finest streams. Eighteen months after opening, this recreational facility, constructed at a cost of almost $1,000,000, was closed and forced into bankruptcy because of the sudden invasion by the submersed weed hydrilla (*Hydrilla verticillata* Casp).

Property values may also be affected by the presence of mosquitoes and other insects, snakes, vermin, dead fish, foul odors, and other conditions associated with excessive growths of aquatic vegetation. Other examples of depreciations in value and damage of property are (1) clogging of navigable streams; (2) washing out of bridges, boat docks, and other structures; (3) flooding and altering of water courses; (4) damage and loss of boats, motors, and other fishing equipment.

Wildlife Management.—Because many species of aquatic plants provide valuable food or habitat for certain mammals, reptiles, amphibians, and birds, the manipulation and control of weed species is basic to wildlife management. Each form of wildlife has specific habitat requirements, and often certain aquatic plants may adversely affect habitat quality. Conversely, some undesirable species of wildlife are attracted to certain vegetation types and must be controlled. Even more important are the preservation and maintenance of habitats of rare or endangered species.

Replacement of solid stands of waterhyacinth or other aquatic weeds with more desirable forms of vegetation achieves the diversity of species required for wildlife habitat affording open areas for resting, food production and foraging, protective cover, and rearing of adult or young aquatic animals and, in particular, migratory waterfowl (Walker, 1969). Public use of wildlife areas requires maintenance of access routes, boat landings, water movement channels, and canals and protection from flooding, safety hazards, noxious insects, and vectors of diseases.

The beneficiaries of these wildlife management programs are the 14,386,000 hunters who spend more than $2,000,000,000 annually, or about $149.46 per hunter, and 85,819,000 recreation days (Anon., 1972). Waterfowl hunters alone averaged $84.47 per hunter and 25,113,000 recreation days. In addition, recreation was provided for 6,813,000 bird watchers, 4,519,000 wildlife photographers, and 26,906,000 nature walkers who spent 411,371,000, 37,828,000, and 337,092,000 recreation days, respectively, in these activities. These activities are critically dependent on aquatic areas and are among the primary concerns of wildlife refuge management.

Fisheries Management.—Environmental quality dictates the existence of acceptable fisheries, and control of plant life is the fundamental basis for fisheries management. Uncontrolled growth of vascular plants and algae can divert solar energy and nutrients from food-chain organisms or other desirable plant life (Walker, 1971). Excessive plant density adversely affects predator-prey relationships, can result in fish kills, block fish migration, inhibit distribution, or engender spawning failures, mortalities of fry-fingerlings, and undesirable changes in water chemistry (Walker, 1964a). Recreational and commercial fisheries are especially affected by high pH, poisonous gases, toxins, low dissolved-oxygen concentrations, various kinds of pestilence, pathogens, and fish food organisms associated with weed growths. Herbicides and algicides promote the stabilization of ecological conditions and are essential in integrated systems of fishery management involving dynamic biological, chemical, and physical environmental factors. Stagnation and degradation of water quality, nutrient availability, and radiant energy often determine the value of fishery habitats, the occurrence of desirable species of fish, and the quality and economic values of recreation and fish products (Walker, 1972).

More than 706 million recreation-days and about $5,000,000,000 ($150 per fisherman) are spent annually by approximately 28 million fishermen (Anon., 1972). By the year 2000 it is expected that the present 82 million acres of inland fishing water will increase to 92 million (Anon., 1962), primarily in the form of warm-water reservoirs, which are subject to the greatest weed problems (Walker, 1969 and 1971). The projected requirement at that time is 680 million fisherman-days for 63 million fishermen (Walker, 1972; Condon, 1968). Thus even more intensive fishery management (and use of pest control chemicals) will be required.

Potable Water Supplies.—Algae, especially the blue-green species, commonly cause undesirable flavors in potable water supplies. Water-treatment processes do not remove these flavors, and the only available recourse is heavy chlorination. Vascular aquatic plants also contribute to the poor quality of potable water. The decay of large masses of dead plants creates pollution conditions similar to those of sewage and industrial wastes. It has been estimated that the oxygen-depleting pollution load of 1 acre of growing waterhyacinth is equivalent to the sewage produced by 40 people (U.S. Congress, 1957). The pollution loads are vastly greater, but of shorter duration, with species that mature and die during short periods within, or at the end of, the growing season.

Navigation.—Interruptions of, and inconvenience to, navigation, except on a limited scale, occur primarily in waters of the Southern and Southeastern United States. The inland waterways of the coastal regions form an extensive network that is vital to the transport of materials to and from the areas. Considerable economic loss occurs when this traffic is delayed or stopped by accumulations of aquatic vegetation. In addition to interference with both commercial and pleasure navigation, there is costly damage to boats and bridges. Drifting mats of waterhyacinth, when piled up against bridge supports, can move and shift the entire structure. Logs and other obstructions concealed by the plants provide additional hazards to navigation. It is estimated that without adequate control of aquatic plants, navigation (and considerable land traffic) would almost cease in these waterways within a 2-year period.

Aquatic Vegetation Management With Herbicides

The management of aquatic weeds is accomplished largely with herbicides at present. Information concerning the total area of aquatic weed infestations and the extent of herbicide use is not available or is fragmentary at best. Twenty states reported the use of herbicides on weed infestations totaling 216,000 acres in 1968 (USDA, 1972). This was almost 2.6 times the area reported treated by 13 states in 1965. The average cost of treatment was $20.50 per acre. These figures are not indicative of the magnitude of the problems, nor do they provide a measure of the total area in which herbicide use would be beneficial.

Algae

Copper Sulfate.—Copper sulfate is widely used to control algae in amost all situations requiring chemical control. The present tolerance for copper sulfate in potable water is approximately 4 ppmw of the crystalline pentahydrate form. This level of treatment is rarely if ever used purposely for algae control. Copper sulfate is toxic to fish, particularly trout, and except in hard water should not be used at rates above 1 ppmw (DeVaney, 1968). It is inadvisable to use copper sulfate in trout waters except when the need for algae removal exceeds the value of the fish that may be killed (Walker, 1969). Rates for the control of blue-green algae range from 0.5 to 1 ppmw; for filamentous algae from 1 to 2 ppmw; and if used as a "slug" treatment in flowing water, 0.3 to 2 pounds per cubic foot of water flow per second. Copper sulfate does not injure crops or other land plants, although it may injure vascular aquatic plants that are used as ornamental plantings. Used at recommended rates, it presents no known hazard to higher animals. Copper sulfate may have an adverse effect on aquatic microfauna, especially where used frequently, continuously, or at heavy rates, particularly in softer waters (Walker, 1969).

Cutrine, a mixture of copper sulfate and triethanolamine, is used to some extent for algae control. It appears to be more effective in hard, or alkaline, waters, where copper sulfate alone does not always give good results. Triethanolamine is reported to prevent or delay the loss of copper sulfate due to the formation of insoluble precipitates. Fish appear to tolerate higher rates of copper in the presence of the amine additive.

Dichlone.—This compound is effective primarily on blue-green algae. Though it is reported to have a very low acute toxicity to warm-blooded animals, it is very toxic to fish (Walker, 1969). It may not be used in potable water. There is very little advantage in the use of dichlone over copper sulfate except in industrial water where the presence of copper is objectionable.

Dichlobenil.—The macroscopic alga *Chara* is especially susceptible to dichlobenil. Because of the cost, it is rarely used for the control of *Chara* alone, although situations do arise where *Chara* by itself is a major problem. The application rates recommended for dichlobenil have been designed primarily for vascular plants; consequently, the minimum effective dosages for the control of *Chara* alone are not defined (DeVaney, 1968).*

Other Herbicides.—Other herbicides that will eliminate all or certain species of algae are acrolein, aromatic solvent, diquat, and endothall (Walker, 1969). These are broad-spectrum herbicides and are usually used to control one or more species of vascular weeds. The control of algae is for the most part incidental to this use. These herbicides are covered in detail in other sections.

Floating Weeds.—Floating weeds are particularly troublesome in the Southern states. The most serious problem species, such as waterhyacinth, alligatorweed, waterlettuce (*Pistia stratiotes* L.), and waterferns (*Azolla* spp., *Salvinia rotundifolia* Willd.), are for the most part from the tropics or subtropics. They do not die back during the winter, although their rates of growth decrease. Hindrances to navigation arise primarily from the excessive growth of floating weeds. With the possible exception of alligatorweed, they are more easily controlled than most submersed vegetation.

2,4-D.—This herbicide can be used at rates of 1 to 4 lb/acre to control most species of floating aquatic weeds. Waterhyacinth is particularly susceptible to 2,4-D and is often treated at rates of 1 to 1.5 lb/acre. Alligatorweed is the most resistant, and treatment rates may be increased to 6 to 8 lb/acre. In addition to being an exceptionally effective herbicide, it is unfortunately hazardous to use in some areas and during some seasons because of the danger that spray and vapors will drift to sensitive crops and ornamental plants. In these instances, substitute herbicides are employed.

There are few proved hazards to animal life due to the direct toxicity of 2,4-D. Modifications in the aquatic environment are due largely to the removal of the aquatic vegetation, and these are generally of short duration. Although a few ester formulations are directly toxic to fish, the greatest hazard to the aquatic environment is the alteration of water quality due to the death and decay of large masses of vegetation after the use of 2,4-D (and other herbicides). The decay of organic matter and the attendant low levels of oxygen result in the suffocation of fish and other aquatic animal life. The subsequent anaerobic fermentation produces high levels of hydrogen sulfide and other metabolites toxic to both animal and plant life. These undesirable effects are experienced only in impounded water or in sluggish moving streams, and they are known to occur frequently from natural causes in waters having precariously balanced ecology states. Residues in water, soil, and fish appear to be short-lived—less than 60 days in the Southeastern United States.

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*See page 119 for additional information on dichlobenil.

Silvex.—The preceding discussion of 2,4-D is equally applicable to Silvex. Although it may be used widely to control floating vegetation, its principal use is as a substitute for 2,4-D in the control of alligatorweed. Field tests have shown that Silvex will provide longer lasting control of this weed. Residues in water, soil, and fish are also slightly more persistent.

Diquat.—Where circumstances make it undesirable or unsafe to use 2,4-D, diquat may be used to control duckweed, waterhyacinth, and waterlettuce. Diquat is injected into the water or sprayed over the surface to control duckweed. It may be sprayed over the water surface or applied by air to control waterhyacinth and waterlettuce. In water containing sediment of any kind, diquat is rapidly adsorbed and inactivated.

When used at recommended rates, diquat is nontoxic to wildlife (Condon, 1968; Heath *et al.*, 1972; Pimentel, 1971; Tucker and Crabtree, 1970), fish, and other aquatic animals (Walker, 1969; Condon, 1968; Pimental, 1971; Battelle, 1971; Lawrence and Hollingsworth, 1969). Its persistence in water is short and usually is reduced to traces in 3 to 4 days. However, a 10-day waiting period after treatment is recommended before use of the water is resumed. The persistence of residues in bottom soils and fish has not been fully investigated.

Submersed Weeds in Irrigation Canals and Ditches.—Aquatic vegetation in irrigation conveyance systems is difficult to control. The water is constantly flowing (usually at a fairly high velocity), which results in the transport of herbicide chemicals from the site of application. To provide adequate contact time for lethal dosages to be absorbed by the vegetation, herbicides must be applied to the water continuously for periods known to be effective. Consequently, large volumes of water must be treated at considerable expense. In addition, herbicides must usually be applied to water that will in a short time be diverted onto cropland. In irrigated areas water is scarce and not to be wasted. During the time when weeds are most troublesome, the canals must operate continuously at full capacity to deliver the volumes of water required to satisfy the needs of the farmers. Thus it is impractical to interrupt the flow of water to cropland by shutting down the flow in the canals or by denying diversion of water to crops. Water not diverted to cropland must be returned to some water system in which herbicide residues might be hazardous.

Acrolein.—Acrolein is usually used as a contact herbicide in large irrigation canals where the use of aromatic solvents is too costly. Application rates vary from about 0.1 to 0.6 ppmw. Treatment times (contact periods) range from 8 to 48 hours. In general, the larger the canal, the lower the treatment rate and the longer the contact period. Infrequently, smaller canals may be treated at rates of up to 15 ppmw for 30 minutes to 4 hours. Irrigation canals and ditches with little grade and very slow moving water may be treated in the same manner as impounded water by injecting 4 to 7 ppmw of acrolein beneath the water surface along the entire length of the canal.

Because acrolein is very toxic to fish (Condon, 1968; Walker, 1969; Battelle, 1971), its use must be restricted to waterways where fish are of minor importance. In addition, treated water should not be permitted to enter other waters until the acrolein has been dissipated. The effects of acrolein on fish and other aquatic organisms have not been fully investigated.

Aromatic Solvent.—Aromatic solvents (almost exclusively xylene of not less than grade B) have been used in irrgation canals with a flow of up to 100 ft^3/sec for more than 25 years. Application rates vary from 6 to 10 gallons per 1 ft^3/sec of water flow applied over a period of 30 to 60 minutes. An emulsifier is added to the xylene (1 to 2 percent) before injection into the water. Xylene is volatile and is lost quite rapidly, making booster applications necessary at intervals of 2.5 to 5 miles.

Aromatic solvents, like acrolein, are contact herbicides and are effective on algae as well as vascular aquatic weeds. They are very toxic to fish, crayfish, and other aquatic animals but have an exceedingly good record of safety to crops and warm-blooded animals (Pimentel, 1971). It is common practice for farmers to continue diverting water onto crops during periods when xylene is used for weed control. Because xylene is used primarily in the smaller canals of water distribution systems, there is usually very little waste or return water: all the water is diverted by the time it reaches the end of the system. Because of its volatility and breakdown of the emulsion during the irrigating process, practically no solvent remains in drainage water (usually very small volumes if any) from irrigated fields. Livestock and other animals refuse to drink water containing more than trace amounts of aromatic solvents.

Copper Sulfate.—The continuous-feed method of using copper sulfate to control submersed aquatic plants has been used only rarely, and mainly on experimental bases. Field trials have shown that 1 ppmw used early in the season, followed by about 0.5 ppmw later in the season when the water is warmer, will control algae and some species of vascular aquatic plants. No acute toxicity to fish has been observed. Chronic toxicity to fish and other aquatic fauna in irrigation systems has not been determined.

Diquat.—The use of diquat in irrigation systems has been restricted to situations where there is virtually no movement of the water. Diquat is ineffective in turbulent water and in water containing appreciable quantities of suspended solids. It is very readily adsorbed to plant or mineral matter, and water residues are usually present in only trace amounts 2 to 4 days after treatment. Although it would probably be safe to use irrigation water 3 to 4 days after treatment with diquat, present restrictions require a waiting period of 10 days. It is not toxic to fish when used at the recommended rates of 0.25 to 1.0 ppmw. Effects on other aquatic organisms appear to be largely indirect and caused by habitat modification.

Endothall.—Restrictions concerning the sites of use of the sodium and potassium salts of endothall are the same as for diquat. Treatment rates vary from 1 to 5 ppmw, depending on the level of weed infestation. The water should not be used for any purpose except swimming for 7, 14, or 25 days after treatment at rates of 1, 3, or 5 ppmw, respectively. Swimming is permitted after 24 hours. Fish may be used for food 3 days after treatment with any endothall derivative. The effects of the sodium salt of endothall on other components of the aquatic environment are largely the result of habitat modification; effects of the alkylamine salts have not been thoroughly investigated.

The alkylamine salts of endothall are more phytotoxic than the inorganic salts, and they are also much more toxic to fish (Walker, 1969). Rates above 0.3 ppmw may cause fish mortality (Walker, 1964a). Both liquid and granular formulations are usually used at 0.5 to 2.5 ppmw—but only for spot treatment or where fish kill is not objectionable. Use of the granular formulation reduces the hazard to fish. Waiting periods for water uses after treatment are 24 hours for swimming, 3 days for use of food fish, and for other uses 7, 14, and 25 days after applications of 0.3, 3, and 5 ppmw, respectively. The effects of the alkylamine salts of endothall on the aquatic environment have not been investigated fully.

Monuron.—This herbicide cannot be used in the main channels of irrigation systems. Its principal use is to control vegetation in lateral ditches that carry water intermittently and directly to irrigated fields. Since herbicides used in these ditches are not linked directly to other water systems, they are of only secondary importance.

Diuron.—The use of diuron is the same as for monuron.

Submersed Weeds in Drainage Ditches.—Many of the factors and conditions governing the uses of herbicides in irrigation canals and ditches apply equally to drainage ditches. In some drainage ditches fish may be of considerable importance, in others they may be nonexistent or of little importance. Also, some drainage ditches may have sizable water flows, while others have essentially no flow during much of the year. Drainage ditches commonly empty into water impoundments or streams. Water from drainage ditches is also used occasionally for irrigation. In treating drainage ditches for control of vegetation, the precautions that must be observed depend on the circumstances of the specific situation.

Acrolein.—Drainage ditches with flowing water are treated in the same manner as irrigation canals. The same precautions should be observed. Drains with little or no water flow should be treated in the same manner as irrigation canals with little flow or with all flow checked (see p. 131).

Copper Sulfate.—May be used infrequently in drainage ditches where the vegetation is predominantly algae. Application rate may have to be increased if treatment is made after algae become heavily matted or if the water is shallow, hard, or alkaline. If there is little or no flow, the entire length of the ditch should be treated. See C1c for precautions and other information.

Other Herbicides.—Diquat, endothall, and aromatic solvent are also used in this application.

Lakes, Ponds, and Reservoirs.—Aquatic vegetation problems are most numerous in lakes, ponds, and reservoirs. It is here that we can anticipate much greater demand for improvement in the environment through the management of aquatic plants. The nation is experiencing wholesale development of almost all available waterfront property. In many areas without natural bodies of water they are being constructed as integral parts of residential developments. At the same time, the recreational uses of water have increased greatly. For various reasons, the quality of water in lakes, ponds, and reservoirs has deteriorated and continues to do so. Algae problems now exist in waters where they were never observed previously. Vascular aquatic weeds frequently pollute and reduce the usefulness of waters valued for generations as favored fishing and other recreational sites. Awareness of the problems, and knowledge that methods are available that may alleviate these even temporarily or in part, will undoubtedly result in pressures to improve the aquatic environment through vegetation management. Permanent solutions, if there are any, must include measures to prevent the pollution and enrichment of the water. In the foreseeable future, significant improvements made in the aquatic environment through vegetation management will probably involve the use of some herbicides.

Dichlobenil.—When used as a broadcast treatment on exposed bottoms or over the water surface, the granular formulation of dichlobenil provides excellent control of vascular aquatic plants and *Chara*. For best results the treatments should be made before or when weed growth begins. Treatment rates recommended are 7 to 10 lb/acre when applied to exposed lake- or pond-bottom soil and 10 to 15 lb/acre when applied through the water. The effects of dichlobenil on aquatic vegetation are usually confined to the actual area treated.

Dichlobenil is not acutely toxic to fish except at application rates 30 to 60 times greater than those recommended for weed control. Whole fish contain residues at levels that approximate those present in the treated water. It is persistent in confined water, and residues have been observed for periods of up to 4 months. For these reasons, dichlobenil cannot be used in potable, irrigation, or livestock water. Fish are not to be used for food or feed for 90 days after treatment.

Diquat.—Application rates of diquat for control of submersed weeds range from 0.25 to 1.5 ppmw, depending on the susceptibility of weeds treated. These rates apply to treatments of entire bodies of water. For spot treatments the rates are frequently doubled to ensure adequate control of the weeds. Combining applications of copper sulfate and diquat are more effective on the more tolerant species of aquatic weeds than diquat alone but must be used with caution in fish habitats. Treatments commonly consist of 1 ppmw each of copper sulfate and diquat. For precautions to be followed and other information concerning the effects of using copper, see p. 129.

Endothall.—The various derivatives of endothall are broad-spectrum herbicides. The disodium and potassium salts are active on most submersed species of aquatic plants (Lawrence and Hollingsworth, 1969; Walker, 1969). They are notably ineffective on *Elodea.* The inorganic salts are used at rates of 1 to 5 ppmw. The higher rates (4 and 5 ppmw) are used for spot or marginal treatments. Fish are not harmed at these rates and may be used for food 3 days after treatment. Because of the short persistence of endothall in water, swimming is permitted after a 24-hour waiting period, and other water uses may be resumed 7 days after treatment with 1 ppmw. The total effects of the sodium salt of endothall are the result of habitat modification (Walker, 1964a and 1972; Condon, 1968). For alkylamine salts of endothall, refer to page 132.

Fenac.—Present uses of fenac are limited to situations in which water can be drawn down to expose the bottom soil of ponds and lakes. Fenac is applied to the exposed soil at rates of 15 to 20 lb/acre. The ponds and lakes should not be refilled sooner than 3 weeks after treatment. Fenac does not appear to be hazardous to fish and other nontarget organisms. Gross observations of treated waters to date suggest that its effects on the aquatic environment are minimal. However, this herbicide is very persistent in water (for as long as 3 to 6 months), and residues in fish have not been fully investigated.

2,4-D.—Various derivatives of 2,4-D are used to control submersed aquatic vegetation (DeVaney, 1968). The most commonly used derivatives are esters, such as the butoxyethanol and isooctyl esters. Less frequently used are the sodium salt of 2,4-D and the amine salts, such as the dimethylamine salt. Because of the real or presumed higher levels of phytotoxicity, the esters have most often been preferred. Granular or pelleted formulations of 2,4-D esters are distributed uniformly over the water surface at rates of 10 to 40 lb/acre. Amine salts are probably more often applied as sprays over the water surface or injected beneath the water surface.

The toxicity of 2,4-D to fish is extremely variable. The ester derivatives as a group are the most toxic. However, the formulating components are an important factor in acute toxicity to fish (Walker, 1964a and 1964b). In laboratory assays, some toxicity to fish occurs at approximately the maximum recommended treatment rates (Lawrence and Hollingsworth, 1969; Walker, 1969). Under field conditions, toxicity at maximum recommended rates has seldom if ever been observed and can be avoided with proper precautions. Any adverse effects on the aquatic environment are primarily the result of habitat modification. Temporary effects are not severe, nor is the damage extensive. 2,4-D should not be used in potable water where the residue would exceed 0.1 ppmw.

Silvex.—The potassium salt of Silvex is applied as a liquid or used occasionally in granular or pelleted formulations (DeVaney, 1968; Walker, 1969). It is, as a rule, somewhat more persistent in the aquatic environment than 2,4-D (Menzie, 1969). It is also slightly more phytotoxic than 2,4-D to some aquatic plants. Because of its greater cost and its limited advantage over 2,4-D, Silvex is seldom used. The recommended application rates are 1.5 to 2 ppmw, or about 5 lb per acre-foot of water. Other observations concerning 2,4-D also apply to Silvex.

Other Herbicides.—Other herbicides used infrequently for the control of submersed weeds in ponds, lakes, and reservoirs are acrolein and aromatic solvents. Because of their toxicity, they are normally used for spot treatments. The discussion on page 131 concerning the use of acrolein and aromatic solvents in irrigation ditches also applies to their use in ponds, lakes, and reservoirs. Simazine and diuron have been used experimentally in extensive testing to control pH and reduce plant biomass responsible for oxygen-depletion hazards in ponds used for fish production. Increases in pH and oxygen levels are highly desirable, and appreciable toxicology and residue research is being conducted on these herbicides to support registration for their use.

Emersed and Marginal Weeds

Emersed weeds are common to shallow bodies of water and shallow, slow-moving streams. Because most are littoral species, they are an important component of the habitat for fish and other aquatic animal life and play an important role in the aquatic food chain. The location of these weeds makes them especially undesirable to lakeside homeowners, swimmers, and other water users.

Marginal weeds are very often grasses or grasslike species. They are often more troublesome than emersed weeds. Many are tall enough to obscure the view of the water, and they impede access to the water. Some are capable of causing severe lacerations, and they provide a habitat for snakes, vermin, and other undesirable animals. If undisturbed, many will encroach on the water surface and prevent the use of much of the surface areas of small lakes and ponds.

Broadleaved Plants

2,4-D.—As a general control for most marginal and emergent broadleaf vegetation, 2,4-D at 2 to 4 lb/acre is commonly recommended (DeVaney, 1968). It is applied in a sufficiently large volume (up to 200 gal/acre) of water to wet the entire exposed plants. For hard-to-wet species of plants with waxy leaves (e.g., as waterlilies, smartweed, waterprimrose, and arrowhead (*Sagittaria* spp.)) better results are obtained by spraying the plants with 2,4-D in oil or in an oil-in-water emulsion (1 to 2 parts oil in 10 to 20 parts water). 2,4-D is applied at 1 to 4 lb/acre in a volume of carrier that will provide a uniform spray cover.

Silvex.—As a general control, Silvex is used in the same manner as described for 2,4-D. Rooted, emersed alligatorweed is treated at 4 to 8 lb/acre. Repeated treatments (three to four) may be required for control.

Grass and Grasslike Species

Dalapon.—Most grasses and grasslike plant species, including cattails and bulrushes, respond well to treatments with dalapon at application rates of 20 to 30 lb/acre. Application should be made before the plants are fully grown and before heading. A large enough volume of water is used to wet the foliage thoroughly. Wetting is aided by the addition of 3 to 4 pints of wetting agent for each 100 gallons of water. Repeated light applications of 5 to 10 lb/acre are more effective on some species of grasses.

Dalapon is registered for use only in drainage ditches and marshes. It is currently replacing amitrole for the control of grasses on ditchbanks and other sites where amitrole was formerly used. Acute toxicity to fish occurs only at very high concentrations (the TL_m concentration for salmon after 48 hours is 340 ppmw) (Lawrence and Hollingsworth, 1969; Pimentel, 1971). Studies to date indicate no adverse effects on the aquatic environment other than those associated with habitat modification (Walker, 1972). No direct effects or residue problems are likely to occur from the concentrations in water following recommended uses.

2,4-D.—Low-volatility esters of 2,4-D applied at 4 to 6 lb/acre in 1:20 oil-in-water emulsions may be substituted for dalapon for the control of bulrushes and cattail (DeVaney, 1968). The volumes of spray recommended to get thorough wetting of the foliage are 150 to 300 gal/acre. As with other grass treatments, the first application should be made at or before heading of the plants. Repeated treatments (three to four) of regrowth may be required for complete control.

MSMA and TCA.—Neither MSMA (monosodium methanearsenate) nor TCA (trichloroacetic acid) is registered for use in or around water. Both have been field tested extensively and appear to have desirable uses for the control of ditchbank grass weeds. At application rates of 20 to 70 lb/acre, TCA controls reed canarygrass; MSMA is the only herbicide that appears capable of controlling johnsongrass on ditchbanks in the Southwestern States where TCA is not effective.

Alternative Methods of Aquatic Vegetation Management

Mechanical Methods.—Various mechanical contrivances have been designed and used in attempts to manage troublesome growths of aquatic plants. Those designed for use in impounded waters and streams are primarily of two types: (1) underwater cutters to sever submersed vegetation and (2) devices for cutting swaths from floating vegetation such as waterhyacinth. Both types have been constructed at various times for simultaneously cutting and removing plants from the water. Simply cutting the plants off at some depth below the surface is not a practical solution. The floating plants drift about, causing new infestations; they continue to hinder use of the water; they float ashore, where they may decay and produce an objectionable appearance and foul odors; and they eventually die and may cause localized fouling of the water that is detrimental to all aquatic animal life.

Harvesters designed to cut and remove plant material from the water have been in existence for many years. The U.S. Army Corps of Engineers pioneered in the design and construction of such macnines. Although effective, they are costly to construct, operate, and maintain. In addition, they are limited to easily accessible waters free of obstructions and to areas they can clear in a given period. Harvested plant material must be disposed of in some manner. Disposal is a serious problem that has not been solved.

The greatest obstacle to mechanical control of aquatic plants in any situation is cost. It was stated recently that "... with existing mechanical harvesters tested to date the cost is as much as $1,600 per acre (depending upon area of use) to eliminate an acre of hyacinth as compared with a chemical treatment cost of about $12 per acre (USACE, 1972). Other estimates for mechanical removal of waterhyacinth range from $150 to $1000 per acre. Harvesters average about 4 acres per day.

Equipment for mechanically controlling aquatic plants in irrigation systems ranges in form from underwater weed cutters and draglines to large chains and disk-type devices. In irrigation systems the principal concerns regarding the use of mechanical methods of control are similar to those encountered elsewhere—cost and the amount of time involved. In addition, the masses of material produced by mechanical control clog screens and trash racks, siphons, headgates, and sometimes water-measuring devices. The operation of sprinkler systems is also seriously affected. The use of chains and disks disturbs the soil and hastens the buildup of silt bars, which when removed by dragline can be very destructive to fish habitats. There is very little good that can be said for the mechanical control of weeds in irrigation systems, drainage ditches, or navigation canals. It is much less desirable in these sites than in impounded waters or large natural streams.

Biological Methods

Fish, Snails, and Other Aquatic Animals.—Herbivorous fish are especially attractive as biological control agents (Avault *et al.*, 1966; Sills, 1970). This is particularly true for species that are acceptable as sporting fish and can be utilized for food. At present very limited use is being made of fish to control aquatic weeds. Florida and California are now using *Tilapia* spp. in a few aquatic sites, but the growth rates and fecundity of the fish may not be desirable. These fish are also sensitive to low temperatures and will not survive winter weather in most areas of the United States.

The most promising of all herbivorous fish tested is the grass carp, or white amur, which is presently undergoing study at several locations (Stevenson, 1965). It tolerates a wide range of temperatures and consumes many different species of plants (Michewicz *et al.*, 1972). It has been cultured in various European and Asian countries for both weed control and food, but little investigation into its ecological impact on other species has been undertaken (Hutt, 1971; Pelzman, 1971). There is a great deal of reluctance and resistance to the release of this fish in the United States because of fears that it may become a troublesome pest similar to the common carp (Sneed, 1971). State workers in Arkansas have made experimental stockings of the white amur in many of the state's natural lakes (Bailey, 1971). Because of its potential as a biocontrol agent, this large fish must be studied carefully and thoroughly by public agencies and released only if it will not present a hazard to the aquatic environment. Its reproduction and growth must be controllable if it is to be used at stocking rates that are balanced in relation to weed growth. As in the case of chemical residues, we can ill afford "biological residues that multiply"; thus the reproduction and distribution of the fish must be strictly controlled.

Various snails also consume aquatic plants. One species that received considerable attention is the marisa snail (*Marisa cornuarietis* L.). It is, like many of the tropical herbivorous fish, very intolerant of low temperatures. Although it avidly consumes aquatic vegetation, it will overwinter in few if any locations in the United States. Mass-rearing techniques developed by the University of Miami under contract with the Agricultural Research Service indicate that the snail could be propagated at a cost of 0.6 cent each if produced at an annual rate of 12 million. The high stocking rates required for the control of aquatic plants make the cost of propagating and utilizing the snail impractical in most waters.

Other aquatic animals, such as the crayfish (*Orconectes causeyi*), have been considered as possible biological control agents. However, only limited tests have been conducted to date, and results are somewhat variable from area to area (Dean, 1969).

Insects.—Although studies in this very important phase of aquatic vegetation management have been minimal, there have been several significant developments in recent years. One was the introduction of the *Agasicles* flea beetle for the control of alligatorweed (Maddox *et al.*, 1971). Since its introduction, it has become established from Georgia to Texas and has become an important factor in the control of this weed. Its range is quite restricted in latitude; however, there is some evidence that by using the beetle in conjunction with chemicals, its effective range may be extended to almost the entire range of the weed.

Other promising insects being released are a species of thrip (*Amynothrips andersoni*) and a moth (*Vogtia malloi*), both parasitic on alligatorweed.

Pathogens.—There is considerable conjecture but little data concerning the role of pathogens in the ecology of aquatic plant communities. Massive kills of aquatic plants are observed periodically. Striking examples occurred recently with Eurasian watermilfoil in estuaries (e.g., the Chesapeake Bay) and with eelgrass (*Zostera marina*) along the Atlantic Coast. The epidemiclike affliction of these weeds led observers to postulate the presence of pathogens (possibly viral). A search for pathogens of several troublesome species of aquatic plants is currently being made by workers at the University of Florida as well as other investigators. The potential and desirability of aquatic vegetation management by the use of pathogens warrants much greater emphasis than is currently given to this area of research.

Competitive Vegetation.—Competition among plants for specific ecological niches often determines the composition of plant communities and the distribution of species. All too often the least desirable species are the most effective competitors. The principle of competition, frequently used in agriculture, is put to good advantage in the management of ditchbank and marginal aquatic plants, where desirable species of grasses are aided by chemicals in establishing positions of dominance. Progress has been made in the last several years in the use of very low growing aquatic species (e.g., pigmyweed (*Tillaea aquatica*) and spikerush (*Eleocharis* spp.)) as competitive plants (Yeo and Fisher, 1970). This research (conducted by the Agricultural Research Service at Davis, California) has resulted in establishing effective control of troublesome aquatic plants in a number of canals and lakes. Because this type of vegetation management reduces or eliminates the use of chemicals, it should receive a high priority in research programs.

Ecological Modification.—Very little research has been done to determine the potential of ecological modification as a tool in the management of aquatic vegetation. Many species exist and thrive within a very narrow range of ecological conditions. Modifying or disrupting a single condition or requirement of the plant may be sufficient to eliminate a species or to reduce the magnitude of its contribution to an undesirable aquatic environment.

Advantages and Disadvantages of Chemical Methods

Efficacy of Chemicals versus Alternatives.—There are few instances in which the efficacy of chemicals has not exceeded that of presently available alternatives for aquatic plant control. Covering or enclosing irrigation distribution systems in pipe is an effective means of eliminating weeds in irrigation canals. At present, the construction of new open systems on U.S. Bureau of Reclamation projects must be justified as alternatives to enclosed systems. Closed systems, though not plagued with weeds, are subject to other problems, such as silting and infestation with clams, bryozoans, and freshwater sponges.

In the narrow band of the Southern United States to which it is climatically suited, the *Agasicles* beetle has proved superior to chemicals for controlling alligatorweed. Outside this narrow range, however, populations of the beetle do not reach the levels necessary to hold alligatorweed in check.

Chemicals remove aquatic vegetation more completely and more quickly than does mechanical control, which is the only alternative method that has or might be used extensively at this time. Underwater cutters and harvesters are unable to clear more than a few acres of weeds per day and are restricted to unobstructed areas. Fixed-wing aircraft, helicopters, and boat-mounted sprayers can treat many times this area. During the mechanical removal of weeds, the plants are usually fragmented. The fragments are often moved about by wind and currents and initiate infestations in new areas. Chemicals are for the most part nonselective in the plants removed. Furthermore, they are difficult to confine to specific areas, and partial treatment of a body of water frequently results in the temporary but total removal of all the aquatic vegetation. Phytoplankton, often as troublesome in some waters as vascular aquatic plants, can be eliminated effectively only by chemicals.

As an alternative to herbicides, water-level manipulation is an effective control measure. Unfortunately, levels in few bodies of water or streams can be varied to this extent. Weed growth in the shallows of some TVA impoundments can be eliminated by manipulating the water levels at certain periods.

Preventing eutrophication and reducing the levels of nutrients in water, although not effective in eliminating plant growth, would reduce the rates of weed growth and the total mass of plant material present in the water at any given time. Most sources of nutrients are runoff from farmland, domestic sewage, and certain industrial wastes. It is unlikely that plant nutrients from these sources will be significantly curtailed or eliminated in the near future.

In spite of current fads for alternative measures, chemical control methods will be necessary as part of any realistic pest-management program that involves integrated systems of mechanical, cultural, biological, or ecological modification as techniques (Walker, 1972).

Environmental Consequences

Agriculture.—The injurious consequences of using herbicides to control aquatic vegetation, insofar as they affect agriculture, are neither serious nor frequent. Because of the proximity to agricultural activities, it would be natural to assume that hazard levels would be greatest in irrigated agriculture. However, after 25 years or more of using such herbicides as copper sulfate, aromatic solvent, and 2,4-D for the control of submersed and marginal weeds in irrigation systems, there have been very few substantiated instances of injury to crops or to livestock. Livestock will not drink water containing potentially harmful levels of acrolein or aromatic solvent.

The residues of other herbicides used in irrigation water are so low that the infrequent and short-term exposures make it virtually impossible for livestock to ingest quantities that would be toxic or cause residue problems in meat, milk, or other agricultural products (Anon., 1968). Similarly, the low levels of 2,4-D, TCA, dalapon, and other herbicides used on irrigation systems (Frank *et al.*, 1970) cause neither injury (Bruns, 1954 and 1957; Bruns and Clore, 1958; Bruns and Dawson, 1959) nor illegal residues in crops (Stanford, 1970; Frank and Demint, 1969/1970 and 1971). Normal weed-control procedures result in the deposition of only a few grams of herbicide per acre; only under experimental conditions involving exaggerated rates of herbicides is it possible to find more than traces of herbicides in irrigated crops. Herbicides are rarely employed in major impoundments of agricultural water. More frequently, they are used in private, multipurpose farm ponds, where the potential for herbicide misuse is greatest. Nevertheless, with proper use and the observance of water-use restrictions after application, the hazards are minimal.

Perhaps the most evident and publicized hazard to the environment is the improper use of herbicides like 2,4-D in the vicinity of susceptible crops and other desirable plants. Problems of spray drift and vapors, though much reduced at this time, were experienced frequently in the past.

Recreation.—The environmental consequences of using herbicides in water are potentially greater for recreation than for agriculture. All water (streams, ponds, lakes, or reservoirs) offers some possibility for recreational use. Because of the wealth of water in most areas of the United States, access to water for recreation was plentiful in the past. The greater population and the development of waterfront property have significantly reduced the opportunities and ease of access. Greater effort is required to improve and maintain the quality of water used for recreation. At present chemical control is the most feasible means of accomplishing this on the scale required.

The consequences of herbicide use may be good or bad. Used properly, herbicides can provide greater expanses of open water for swimming, boating, skiing, fishing, and other activities. They can to some extent retard the process of eutrophication and extend the useful life of lakes and ponds. Vegetation that aids the breeding of mosquitoes and harbors other insects, as well as snakes and vermin, can be removed, with subsequent improvement of the aquatic environment for recreation.

Adverse or controversial effects on certain recreational uses of the aquatic environment can be anticipated. By management of the aquatic vegetation, water may be converted from such uses as fishing or waterfowl habitat to water used primarily for swimming, boating, and skiing. Such conversions raise controversy due to conflicts of interest depending on the recreational needs or desires of individuals. The control of aquatic plants with certain herbicides requires the interruption of some water uses for specific periods, usually when the recreational needs for water are greatest. This is a major inconvenience to vacationers.

Persistent use of herbicides may have long-term effects on the ecology of aquatic sites. These ecological systems are exceedingly complex and variable even when unmolested. The ecological modifications resulting from the use of herbicides may be far reaching and at this time can only be surmised.

Fisheries Management.—Without the use of chemicals for controlling the growth of aquatic plants, the ecological consequences related to fisheries management can be disastrous (Walker, 1971). Usually, the ecological succession of aquatic plants results in the overwhelming predominance of a few plant species that exhibit a pattern of seasonal succession. The primary purpose of herbicide use is to modify plant succession and the seasonal distribution of biomass and its species composition (Walker, 1972). When this vegetation becomes dense, there is always a high probability of summer or winter fish kills as a result of oxygen depletion when the plants die and decay (Walker, 1969).

Direct toxicity to aquatic animal life is not a serious problem with most herbicides or algicides (Condon, 1968; Lawrence and Hollingsworth, 1969; Walker, 1969; Tucker and Crabtree, 1970; Battelle, 1971; Pimentel, 1971). Fish and many other aquatic fauna vary in their sensitivity to low oxygen tension, and to poisoning by hydrogen sulfide, ammonia and a variety of other nitrogenous compounds, and other products of decomposition.

Very few alternatives to chemicals exist for effective plant control (Walker, 1969). Mechanical control with weed cutters is restricted to unobstructed areas and to deeper water. Mowing fragments many species, causing more propagules to be formed; this provides an advantage to weeds that are capable of rapid regrowth and establishing dominance over other species. The cultivation of monospecies vegetation is an adverse ecological consequence that is just as serious as no control. The removal of plant biomass by mechanical means has the distinct advantage of interrupting nutrient recycling, thus decreasing the burden of decomposed organic matter (and the attendant oxygen depletion), the deposition of organic debris, and the processes of eutrophication. Biological control, where effective, is advantageous in that nutrients are recycled into other food chains. Such recycling is most desirable when it leads to the production of food that can be harvested or contributes directly to greater recreational use of water. However, the most realistic approaches to aquatic plant control require the integrated use of chemical, mechanical, and biological methods that provide satisfactory long-term management of the troublesome aquatic vegetation.

Wildlife Management.—The ecological consequences of controlling aquatic plants by chemical means may affect wildlife indirectly by modifying the habitat. Chemical control may have an adverse effect if it destroys plants that are valuable for food, nesting, rearing, roosting, or protection. Mechanical control can be far more disruptive than chemicals with respect to the needs and activities of wildlife. The temporarily adverse effects of herbicide chemicals on water quality and the growth, regeneration, and general suppression of the plant biomass may be more critical for some wildlife species than others. Thus particular care must be taken in areas where habitat preservation is required for the welfare of rare and endangered species. Direct toxicity of herbicides to wildlife has never been a problem (Condon, 1968; Lawrence and Hollingsworth, 1969; Tucker and Crabtree, 1970; Battelle, 1971; Pimentel, 1971); however, we have insufficient data with respect to residues and their biological significance. Similarly, the adverse effects of mechanical control and biological control agents have not been evaluated critically.

Property Values.—The value of waterfront property would be enhanced by the use of herbicides to control serious infestations of floating, submersed, or marginal aquatic weeds. The principal concern of property owners is that the water be clean and open; other attributes rarely have greater priority.

Potable Water Sources.—Eutrophication processes take their toll on the quality of potable water. Very often this is demonstrated first by the abundance of algae. Infestations of algae can be managed successfully with a carefully planned program employing copper sulfate. Storage lakes and reservoirs not previously containing excessive growths of vascular aquatic plants are now experiencing an increasing abundance of these weeds. Also, the increasing need for potable water has forced the utilization of less desirable water sources. Large quantities of vascular weeds have a strong polluting effect during certain times of the year. These circumstances have forced the use of herbicides, in addition to copper sulfate, in a number of sources of potable water. This practice or more extensive use of mechanical harvesters will increase as weed problems become more severe.

Navigation.—Large quantities of herbicides are used in the Southern States to keep waterways open to navigation. It is estimated that, if chemical control were discontinued, within a 2-year period a high proportion of these waterways would no longer be navigable. During the past 2 years the U.S. Army Corps of Engineers, at the request of certain groups and individuals, carried out a modified chemical weed-control program on the St. Johns River in Florida. Only selected areas and infestations of waterhyacinth were treated with herbicides. This program, combined with a mild winter (1971-1972) that permitted greater than normal growth of hyacinth, resulted in an infestation that by the summer of 1972 was completely out of control. It was estimated that 10,000 acres or more of waterhyacinth were descending the St. Johns River. Navigation in some areas was totally blocked; it was reported that bridges were in danger of being carried away; and the fishing industry in much of the area was disrupted. Navigation in the waterways of more northerly states may be impeded by weed growths; however, the problems are less serious and are usually limited to the smaller waterways and portions of water impoundments.

The use of herbicides to clear navigable waters has favorable environmental consequences insofar as navigation is affected. There are numerous and persistent complaints that chemical control programs seriously impair fishing. Some complainants state categorically that the herbicides poison the fish. Although sinking mats of dead or decaying vegetation do cause oxygen depletion and release noxious gases and metabolic products, the residues of aquatic herbicides have rarely been found to be poisonous. There is little doubt that the removal of weeds affects fishing and particularly fishing customs. The disappearance of weeds alters the habitat as well as the source of fish food (Walker, 1969). In large water systems this causes major shifts in fish populations and densities, which are frequently mistaken for direct chemical effects on the fish (Walker, 1972). Deleterious effects on the fish and fishery may occur. These are likely to be indirect and may be quite complex. Because aquatic ecology is exceedingly complex, there are no quick or easy answers to questions regarding the overall or long-term effects of herbicides on fish or other aquatic fauna.

Herbicide Residues in Water

Control of Submersed Weeds.—The initial concentrations of herbicides used in water to control submersed weeds are usually determined before treatment. If the water volume and area are carefully measured, the concentrations are usually within an acceptable range of error. The concentrations employed are determined by the particular herbicide used and the species of plants being treated. The more commonly used herbicides and recommended application rates are listed in Table 6. Data from some of the more typical studies on the dissipation of herbicide residues in water are compiled in Table 7.

Table 6. HERBICIDES AND APPLICATION RATES RECOMMENDED FOR THE CONTROL OF SUBMERSED AQUATIC WEEDS

Herbicide	Form	Application rate[1]
Acrolein	Liquid	0.1 to 0.6 ppm[2] 4 to 7 ppm[3]
Aromatic solvents	Emulsified	600 to 740 ppm[4]
Copper sulfate	Pentahydrate	0.1 to 2 ppm
Dichlobenil	Granular	10 to 15 lb/acre 0.9 to 1.4 ppm[5]
Diquat	Cation	0.25 to 1.5 ppm
Endothall	Disodium salt Amine salt	0.5 to 4 ppm 0.05 to 2.5 ppm
Fenac	Granular	15 to 20 lb/acre 1.4 to 1.8 ppm[5]
Silvex	Potassium salt	1.5 to 2 ppm
2,4-D, ester	Granular	20 to 40 lb/acre 1.8 to 3.6 ppm[5]

[1] Source: USDA (1969). Application rates are in terms of acid equivalent or active ingredient.

[2] For extended application time in flowing water.

[3] For treatment of weeds in quiescent water.

[4] Emulsifier added at concentrations of 1.5 to 2 percent.

[5] Parts-per-million concentration arbitrarily expressed in terms of 4 feet of water.

Table 7. RESIDUE DISSIPATION IN PONDED WATER AFTER HERBICIDE APPLICATION

Herbicide	Application rate (ppm)	Concentration detected			
		Highest		Final	
		ppm	Days	ppm	Days
		Liquid applications			
Amitrole[1]	1.0	1.34	1.0	0.08	201
Fenac[1]	4.0	5.2	1.0	2.4	202
Diquat[1]	2.5	3.27	2.0	N.D.	30
Paraquat[1]	2.1	1.05	1.0	N.D.	38
2,4-D, methylamine salt[2]	1.5	0.139	1.0	0.004	41
Silvex, PGBE ester[3]	2.9	1.6	7.0	0.02	182
Diquat[4]	0.62	0.49	1.0	0.001	8
Paraquat[4]	1.14	0.55	1.0	0.001	12
Endothall[4]	1.0	0.18	2.0	0.001	36
Copper[5]	0.50	0.42	0.1	0.19	3
Endothall[6]	1.2	0.79	4.0	0.54	12
		Granular applications			
Dichlobenil[4]	0.58	0.32	36	0.004	160
	0.40	0.23	8	0.001	160
Fenac[4]	1.56	1.61	18	0.38	160
	1.0	0.71	8	0.07	160
2,4-D, butoxyethanol ester[4]	1.33	0.067	18	0.001	36

[1] Data from Grzenda *et al.* (1966).
[2] Data from Averitt (1967).
[3] Data from Cochrane *et al.* (1967).
[4] Data from Frank and Comes (1967).
[5] Data from Toth and Riemer (1968).
[6] Data from Yeo (1970).

Some of the more effective herbicides are also among the more persistent (Menzie, 1969). The excellent and often complete control of weeds by fenac and dichlobenil may be attributed in part to the persistence of these herbicides. Diquat, 2,4-D, and endothall disappear from water at rapid to moderate rates. Although rapid dissipation from water is desirable from the standpoint of residues, it may impair or destroy the efficacy of some chemicals (e.g., diquat) when used in water containing sediment or organic matter. In some instances, the dissipation of herbicides from water may be accompanied by accumulation of high concentrations of the herbicides in the soil (Frank and Comes, 1967).

The dissipation of herbicides in the flowing water of canals and streams has not been studied extensively. However, from experiments carried out during the last several years (Frank *et al.*, 1970), it is apparent that the dissipation (in flowing water) of freely water soluble herbicides not extensively sorbed from water solutions is affected principally by dilution. For nonvolatile herbicides, extrapolation of residue and dissipation data (Table 8) indicates that for most canal-bank treatments for marginal weeds, the herbicides that enter the water dissipate to trace levels after a waterflow of about 20 miles.

Table 8. MAXIMUM LEVELS OF HERBICIDE RESIDUES FOUND IN IRRIGATION WATER DURING DITCHBANK TREATMENT[1]

Herbicide and canal treated	Treatment rate (lb/acre)	Water flow (ft^3/sec)	Maximum concentration of residue (μg/l)
Dalapon:			
Lateral No. 4	6.7	290	23
Manard lateral	9.6	37	39
Yolo lateral	10.5	26	162
TCA:			
Lateral No. 4	3.8	290	12
Manard lateral	5.4	37	20
Yolo lateral	5.9	26	69
2,4-D, amine salt:			
Lateral No. 4	1.9	290	5
Manard lateral	2.7	37	13
Yolo lateral	3.0	26	36

[1] Source: Frank *et al.* (1970).

Data showing residue levels and dissipation rates typical of aromatic solvent (xylene) treatments in irrigation canals are given in Figure 1. The persistence of acrolein residues appears to be temperature dependent, but very few accurate determinations are available. The loss rates of acrolein from concentrations of 0.6 and 0.7 ppmw in a canal with a flow of 132 to 135 ft^3/sec were determined to be 98 percent from 64°F water after a waterflow of 19 miles and 62 percent from 48°F water after a flow of 27 miles (Battelle, 1970).

Control of Floating Weeds.—Residues in water due to the application of herbicides to floating weeds are difficult to determine. On the basis of the rates of application and the depth of water, total possible residues may be calculated. These are seldom realistic because the vegetation intercepts a significant fraction of the total herbicides applied. Residues of amine salts of 2,4-D and Silvex in water are highest 1 to 2 weeks after the treatment of alligatorweed (Averitt, 1967). Almost all published data concerning residues in water from the treatment of floating vegetation show that even at high rates (8 lb/acre), residue levels will usually be less than 1.5 ppmw.

Potable Water.—Only two herbicides have been assigned tolerance levels in potable water: 2,4-D amine (0.1 ppmw) and copper sulfate (1 ppmw copper ion). This level of copper sulfate is higher than that used in most instances for algae control. The level of 0.1 ppmw of 2,4-D would very likely be exceeded in most instances when used for the control of aquatic plants. Possible exceptions might be low rates (1 to 2 lb/acre) sprayed on solid mats of floating weeds (e.g., waterhyacinth). Consequently, 2,4-D or other herbicides should be used under circumstances that will permit dissipation to acceptable levels before the water reaches outlets to water-treatment plants.

Fish and Wildlife.—Herbicides residues are seldom found in fish collected from the wild, but very few analyses have been specifically directed toward their detection (Walker, 1964b, 1969, and 1971). As a group, herbicides are less persistent than organochlorine insecticides (Stickle, 1968). They do not "biomagnify" as readily in food-chain organisms or cause high residues in fish because they have a different partition coefficient or fat solubility (Walker, 1964b; Grant and Schoettger, 1971). In the most severe cases of herbicide-residue accumulations in fish, the levels are usually

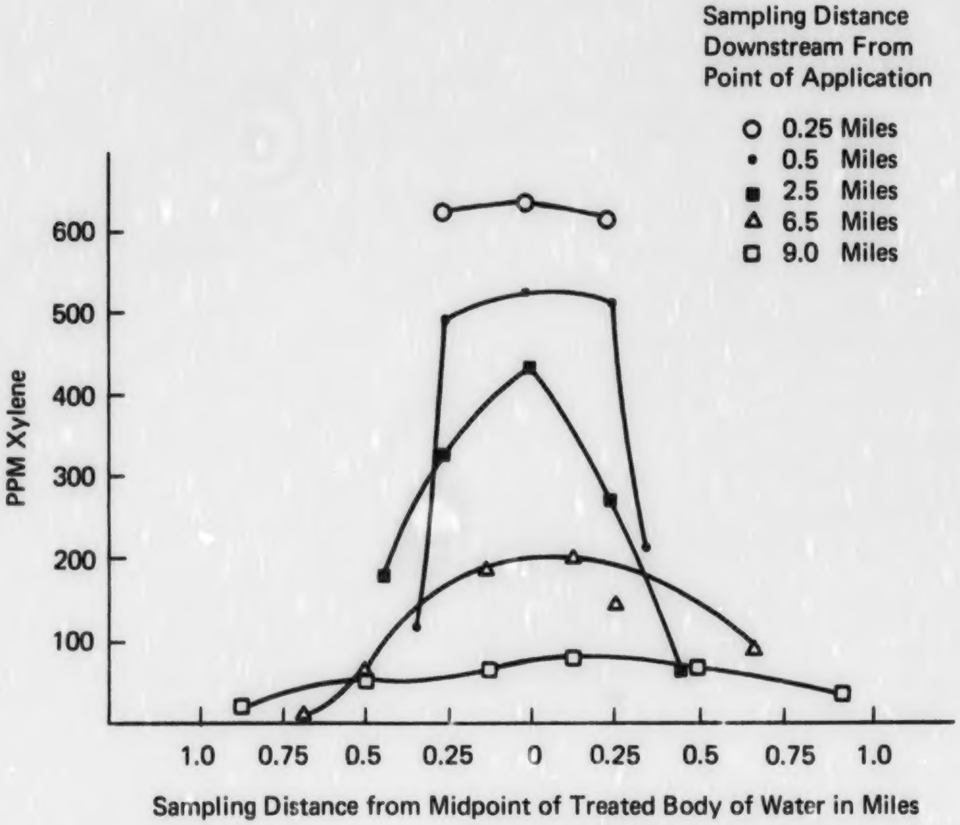

Figure 1. Graphic illustration of the longitudinal dispersion of a 700-ppm application of xylene. The effect of dilution and "stretch-out phenomenon" reduced the concentration at sampling points downstream as measured with reference to the midpoint of application in the stream flow.

quite comparable to the concentrations in the water, and they dissipate rapidly as the source diminishes (USDA, 1963; Walker, 1972). Such is the case with dichlobenil, simazine, diuron, 2,4-D, and Silvex. Fish can hydrolyze or metabolize most herbicides, and the metabolites, conjugates, and breakdown products are readily excreted (Walker, 1964b; Menzie, 1969). Residues have not yet presented problems in other wild animals but would be expected to follow patterns similar to those observed in livestock and poultry (Menzie, 1969).

Crops.—Illegal or unacceptable residues in crops stemming from the use of water containing herbicides have not been a problem. Herbicide concentrations high enough to produce significant levels of residues in crops would very likely kill the crop plants, particularly those that are irrigated with sprinkler systems. Some data on the levels of residues in crops irrigated with water containing herbicides are shown in Table 9. The concentrations of herbicides were usually below the minimum levels of detection. Where residues were detected, they were below the tolerances now established for them in food and feed crops.

Livestock.—Most herbicides ingested by livestock are excreted in a short time. Unlike insecticides, they do not accumulate in fats; consequently, there is no buildup of residues. Ingestion in sufficient quantities may result in residues in milk and eggs. Except for aromatic solvent, recommended uses of herbicides produce residues in water ranging from a fraction of 1 ppm to several

Table 9. RESIDUES IN CROPS IRRIGATED WITH WATER CONTAINING HERBICIDES[1]

Crop and method of irrigation	Residues in crops (ppm)				
	Dalapon (0.1-2.5 lb/acre)	Diquat (0.10-0.5 lb/acre)	Dichlobenil (0.1-0.5 lb/acre)	2,4-D (0.05-0.25 lb/acre)	Silvex (0.05-1.5 lb/acre)
Carrots:					
Furrow	0.56	<0.05	<0.05	0.03	<0.05
Sprinkler	0.42	<0.05	<0.05	0.06	<0.05
Grain sorghum:					
Furrow	0.05	<0.10	<0.02	<0.05	<0.05
Sprinkler	0.11	<0.10	<0.02	<0.05	<0.05
Lettuce (Romaine):					
Furrow	0.88	<0.05	<0.01	0.14	<0.05
Sprinkler	1.13	<0.05	<0.01	0.11	<0.05
Onions:					
Furrow	0.46	<0.05	<0.02	<0.01	0.03
Sprinkler	0.67	<0.05	<0.02	<0.01	0.03
Potatoes:					
Furrow	0.03	<0.05	--	0.03	0.03
Sprinkler	0.04	<0.05	--	0.05	0.04
Soybeans:					
Furrow	0.20	<0.10	<0.05	<0.05	0.14
Sprinkler	0.20	<0.10	<0.05	<0.05	0.11

[1] Source: Stanford Research Institute (1970).

ppm. At these concentrations, it is virtually impossible for livestock to consume large enough volumes of water to accumulate residues.

Toxicity Hazard

Livestock.—To date there have been very few proved cases of livestock poisoning from any pesticides and even fewer cases involving aquatic herbicides. The instances of toxicity reported were attributed to human negligence or accident.

Fish.—Information on the toxicity of herbicides to fish and other aquatic organisms is mainly derived from laboratory bioassay tests involving sterile, artificial environments (Lawrence and Hollingsworth, 1969; Walker, 1969; Pimentel, 1971). These tests are rarely conducted in the presence of aquatic vegetation, soil, suspended sediments, and other substances that interact in the absorption/desorption kinetics or in degradation/detoxification mechanisms (Walker, 1964b). Conversely, less-informed individuals may also translate TL_{50} values and toxicity measurements from short-term bioassay tests into "safe" concentrations when these data are not applicable and certainly not to be misconstrued as "ecologically safe or nonhazardous" (Grant and Schoettger, 1972). Compared to other pesticides (insecticides, fungicides, etc.), herbicides are much less toxic to fish and aquatic fauna (Walker, 1964b; Grant and Schoettger, 1972). When used according to directions, presently labeled herbicides seldom cause extensive or lasting injury to nontarget organisms in fish habitats (Walker, 1972). Care must always be exercised to ensure that too large a mass of dead or dying vegetation does not deplete the supply of dissolved oxygen or result in an excessive production of toxic gases (i.e., hydrogen sulfide) or other toxic byproducts (ammonia, hydroxylamines, etc.) (Walker, 1969).

Some fish kills can result from the direct toxicity of herbicides like acrolein, dichlone, xylene (petroleum distillates), alkylamine salts of endothall, and combinations of copper with diquat or endothall when used without regard for fishes (Walker, 1969; Pimentel, 1971). Even here, partial treatments that allow for adequate dilution, buffer zones, and care in driving fish out by initiating treatment at lower concentrations that repel fish will avoid many toxicity problems (DeVaney, 1968). The selection of less toxic formulations, such as the amine salts of 2,4-D rather than the more toxic esters, can minimize hazards to fisheries (Walker, 1964a).

Water volumes, rates of flow, circulating currents, tidal action, and other simple factors are important considerations in the use of herbicides (Walker, 1969). Unfortunately, placement of herbicide on the target is difficult and is a basic problem in avoiding hazardous effects on nontarget organisms (Walker, 1964b; Pimentel, 1971). However, newer developments in granular formulations, encapsulations, and other slow-release formulations permit on-target application with longer herbicide-contact time and lower levels of exposure to fishes, shellfishes, and other nontarget organisms. Direct conflicts of purpose sometimes occur when algicides destroy valuable plankton species or when some aquatic plant growth is desirable for fish-food organisms. These instances of conflict involve the total elimination of vegetation by nonselective herbicides (Walker, 1964b).

Wildlife.—As with fish, the toxicity of herbicides to wildlife is not direct but is related to the indirect effects of habitat modification. The drift of herbicides onto desirable marginal vegetation or contamination of water flowing into waterfowl-food-bearing areas are obvious problems that can be avoided by proper management. Direct conflicts do exist when valuable waterfowl foods (such as pondweeds, naiads (*Najas* spp.), and duckweed) are the targets of herbicide application. Thus nesting cover or critical food organisms for young birds are destroyed, and failures in reproduction occur in the treated area. Destruction of protective cover may open up areas, leaving wildlife vulnerable to predation. Moreover, some pathogenic organisms may thrive under the septic conditions produced by decaying vegetation.

Crops.—For algae control copper sulfate is used most frequently at concentrations that are no greater, and often lower, than the tolerance level established for this herbicide in potable water (USDA, 1963). Xylene is a common formulating ingredient for many pesticides and as such is often applied directly to crop plants. The distribution of irrigation water containing acrolein by furrow or sprinkler contributes to the rapid loss of this herbicide. Copper sulfate, xylene, and acrolein are of minor importance as sources of toxicity to crop plants.

When used as directed, other herbicides are present in irrigation water at levels that are not toxic to crops. We can calculate the maximum amount of a herbicide like 2,4-D that might be applied to cropland after its use on an irrigation canal bank. Water from a 4-mile-long body of irrigation water flowing at a velocity of 1 mph could be diverted onto an adjacent field for 4 hours. A diversion rate of 2 acre-inches of water in 10 hours would result in the delivery of 0.8 inch of contaminated water (4 hours at the rate of 2 inches per 10 hours) per acre. An 0.8-inch depth of water containing 50 ppb of 2,4-D (a higher concentration than that usually observed) would deposit slightly less than 0.009 pound of 2,4-D per acre of cropland. Residue levels of much greater magnitude have not caused injury to irrigated crops.

The manner in which irrigation water containing herbicides is applied to cropland may influence the levels of herbicides that are toxic to crops. Obviously, sprinkler irrigation of crops like lettuce and sugar beets with water containing 2,4-D will result in toxicity at lower levels of contamination than would occur if the water were applied by furrow. Considerable data have been published concerning the toxicity of herbicides in irrigation water (Bruns, 1954 and 1957; Bruns and Clore, 1958; Bruns and Dawson, 1959; Averitt, 1967). Other studies are in progress or have been completed but not yet published.

Social and Economic Impact of Restricting the Use of Aquatic Herbicides.—With the exception of copper sulfate, the aquatic herbicides currently being used are organic in origin and are not persistent in the aquatic environment. Rarely do they accumulate in animals, and there is little evidence of biomagnification—in contrast to many insecticides. Occasionally continuous use of copper sulfate has resulted in the accumulation of copper in aquatic sediments, with deleterious effects on the bottom-living aquatic fauna.

Changes in the aquatic environment do occur, and some injury to nontarget organisms results from the use of herbicides. This injury is almost always due to secondary effects (modification of the habitat) or to anaerobiosis after the death of large masses of aquatic vegetation. At the same time we frequently observe similar occurrences arising spontaneously from natural conditions in certain bodies of water. The question of whether or not to restrict the use of aquatic herbicides rises with increasing frequency. Although most opinions are based on a sincere regard for the welfare of the aquatic environment, they are too often expressed without knowledge or consideration of the consequences. To begin with, there is little doubt that aquatic vegetation will become increasingly troublesome. This is due to the increasing demands made on available water resources, the multiple uses of water, and the increasing burden of nutrients being supplied to natural waters. Many uses of water are now dependent on some form of aquatic vegetation management and will become more so in the future.

Irrigated agriculture would suffer a severe blow if denied the use of herbicides. Even with the use of herbicides, operation costs have risen steadily and would increase sharply if irrigation operators were forced to return to mechanical methods. Many farmers could survive only if the prices of farm commodities were proportionately increased. A recent Bureau of Reclamation decision resulted in a return to mechanical control methods on the Fort Hall Indian Irrigation Project in Idaho. The annual cost of weed control on this project will rise from $12,000 to $134,000 (USDI, 1972). In addition, many farmers obtained insufficient water to mature crops after the change to mechanical control, and costs for removing silt from sprinkling equipment were as great as $4000 per farmer. Other difficulties and costs involved the maintenance and repair of silt-damaged pumps, clogged pipes and screens, choked headgates, etc. The irrigation season would be drastically shortened without chemicals for weed control. Estimates have shown that, without the use of herbicides, farmers on irrigated land in the West would be out of water by July 15 of any growing season.

If federal and state agencies were denied the use of herbicides, navigation on many of the southern streams would very likely cease within 2 years.

Recreation and property values would be restricted and depressed due to the reduction in water quality. Many important deleterious effects that would follow restrictions on the use of aquatic herbicides could be listed. However, any activity requiring open water and freedom from masses of aquatic vegetation would be adversely affected.

In the absence of aquatic herbicides, the demands for usable water of good quality would very likely create increased interest in the fields of mechanical harvesting and biological control methods. The first, though limited in practical application to many waters, can be accomplished, but at much greater expense. The development of biological controls is a slow process; present opinion is that, although biological control is desirable and helpful, by itself it will not solve many of the aquatic weed problems.

Overall, the effect of restrictions on herbicide use would be as follows:

1. To reduce the quantity of acceptable water available for various activities and consequently more intensive use of these

2. To increase the need and demand for mechanical control regardless of cost

3. To increase the expense of vegetation management

4. To increase the cost of living through more costly food and recreation

5. To reduce the level of acceptability of water quality and opportunities for recreational and other uses of water

On the positive side we can assume some reduction in the level of water pollution from the use of herbicidal chemicals. If some chemical operations do in fact reduce the quality of fishing, some improvement should be expected. The hazard of unknown and long-term deleterious effects of aquatic herbicide use on the environment would be eliminated along with attendant residues.

Training Requirements for Users.—Because the aquatic environment is complex and misuse of chemicals could be far reaching, users of aquatic herbicides should have adequate training and experience. Many states are now employing a permit system of use. Issuance of permits probably will be done locally by a professional agriculturist, fish and game warden, or other employee who has training and experience in the field. Users in public waters should be trained, professional, custom applicators or qualified state employees. Users of aquatic herbicides in private waters would require no specific training or experience. However, in these instances, the trained individual issuing the permit should ensure that the proposed use is safe and reasonable and that the user is aware of and will follow labeling and other restrictions.

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CROPS

Introduction

Man's survival and standard of living depend on his manipulation of the environment to produce an ecological situation favorable to the growth of crops. Weed control is one of the major environmental manipulations necessary for the efficient and economical production of crops (NAS, 1968, p. 254).

Weed control in crops is an extremely broad and complex problem. Target weed species include annuals, biennials, and perennials with large differences in rooting depth, heights, spreading habit, etc. Also included is a wide range of plant types such as ferns and thousands of different angiosperms, both monocotyledons and dicotyledons. Because crops are grown under such a variety of conditions, weed species in those crops also vary widely. They can include both terrestrial plants and, in the case of rice, aquatic plants.

Weeds growing in cropland interfere with production of the desired crop. This can result from *competition* for light, moisture, and nutrients. In some cases, it may involve *allelopathy*, that is, growth inhibition caused by chemicals produced by the weeds. These effects lead to a reduction in crop yields. Weeds can also reduce the *quality* and *marketability* of crops. For example, wild garlic in wheat will impart an unpleasant flavor to the flour, and downy brome in alfalfa will reduce the value of the hay produced. Weeds can interfere with harvest operations. Green weeds in grain crops may cause heating and spoilage of the grains during storage. Weeds can harbor diseases, insects, and rodents that attack crop plants.

Hundreds of commercial crops, such as solid-seeded small grains, row crops, and orchards, are grown in the United States. Some crops are annuals, others are perennials. Furthermore, environmental conditions and weed problems differ markedly across the country even within the same crop. These wide differences obviously necessitate the use of different weed control practices, including herbicides. One particular herbicide may work efficiently in a specific crop in one state but not in another. Also, continuous use of the same herbicide in a given location results in a buildup of resistant species or types (Ryan, 1970). These factors have led to a demand for a wide array of herbicides.

Losses due to weeds can be severe. In the United States, rice yields were reduced by an estimated 17 percent each year from 1950 to 1961, resulting in an annual loss of $46 per acre (USDA, 1965). Uncontrolled weeds have reduced corn yields by over 90 percent (Behrens and Lee, 1966). Similarly, weeds in sugar beets have reduced yields by 90 percent or more (Dawson, 1965; Zimdahl and Fertig, 1967). Many examples could be cited.

Growers have benefited greatly from the introduction of new methods of weed control, including herbicides. These benefits are largely in the form of increased yields and reduced costs of production. From 1961 to 1969 rice yields increased approximately by 900 lb/acre, representing an approximate value of $90,000,000 for 1969 alone (USDA, 1973). A significant portion of that can be attributed to improved weed-control measures, through the increased use of herbicides. During the last decade the amount of hoe labor in cotton production was reduced from 48 to 13 man-hours per acre in certain areas of the United States by the use of herbicides. The cost of labor for weeding strawberries has decreased from as much as $200 to as little as $16 per acre where selective herbicides are used in combination with tillage and cultivation (NAS, 1968, p. 255). Benefits from using herbicides may last more than 1 year. One study (Dotzenko *et al.*, 1969) has shown that chemical weed control reduced the population of weeds compared to mechanical cultivation. This would result in fewer weed seeds in subsequent years.

Although there has been a turnover in the herbicides available for use in specific crop situations, there is an increasing fear among farmers that there will eventually be a loss of usable herbicides for a crop situation for which there is no effective alternative. Research workers in North Dakota (Nalewaja, 1971) estimate that if the use of 2,4-D and MCPA were discontinued for wild mustard control in cereal grains and flax, an annual economic loss of $175 million would be sustained. These herbicides are the only feasible method now available for controlling wild mustard in these crops. During the last 20 years, the use of 2,4-D to control weeds in an accumulated 460 million acres of wheat increased the yield by about 2 billion bushels, valued at $3.25 billion.

In 1971, (Delvo, 1971) conducted a study to evaluate the economic impact of three herbicide-use restrictions on typical cash-grain farms in 17 counties in Nebraska. He considered both herbicidal and nonherbicidal control procedures. The return to the operator for labor and management ranged from $1900 on a 400-acre dryland farm to $7700 on a 640-acre irrigated farm when preemergence herbicide treatments and cultivation were used to control weeds. Economic returns dropped to $550 and $1700 for these two farm situations when only preemergence herbicide treatments were used, and were negative when only cultivation was used to control the weeds. This points out the vulnerability of our present farm units if only one of their major production tools (herbicides) is restricted.

Questions about the environmental impact of herbicides often revolve around their persistence in the soil. It is frequently thought that any persistence in itself is detrimental to the environment. This is not necessarily true. Under some situations the persistence of a herbicide used on agricultural cropland can actually result in decreased potential environmental damage. There are occasions when a short-term or short-persistence herbicide is most advantageous and would result in less potential environmental contamination. There are other situations when the use of a longer persisting herbicide would result in less risk for environmental contamination. To produce a crop economically the farmer must be able to grow the crop without weeds in the early part of the season to prevent competition, and without weeds in the late part of the season to harvest a high-quality crop economically. If the environmental conditions are such that there is a potential for continual weed germination and development through the season, the use of a persistent herbicide that would last in the field as long as the crop could provide the most economical and most environmentally safe situation. In such a situation only one herbicide would be used during the growing season instead of several. If such a persistent herbicide could not be used, it might be necessary to use a diversity of herbicides at several application times, with resulting greater potential for environmental contamination with each application.

The 1967-1968 market basket survey conducted by the Food and Drug Administration revealed a total herbicide intake of the herbicides monitored of 0.00006 mg/kg of body weight per day. Thus it would take 670 years for a 150-pound person to consume 1 gram of herbicides from his food (Corneliussen, 1968; Duggan and Lipscomb, 1968). The average daily intake of herbicide residues dropped from 0.00006 mg/kg of body weight per day in 1968 to 0.000008 in 1970—a drop of 86 percent (Duggan and Corneliussen, 1972). Since man is at the end of the food chain, biomagnification of herbicide residues in food does not appear to be a problem. Soil, crop, water, sediments, wildlife, and air samplings for herbicide residues rarely show significant amounts. This is probably because herbicides are usually applied only once a year and most herbicides are short-persistence pesticides. Herbicides have a built in warning system in that any accumulation in soils would be visually evident because of their phytotoxic effects on susceptible plants.

Organic herbicides have not accumulated in the environment (Sheets and Kaufman, 1970). Their persistence in soils and in plants is relatively short. They are eliminated from the bodies of animals in a short time as has been shown in extensive data developed for the registration of herbicides. There have been few problems with wildlife and other species resulting directly from the use of herbicides. The dominant effect of the use of herbicides is to alter the botanical composition of an area; a secondary impact may occur as a result. Problems with the persistence of herbicides in soils as reported in USDA, 1972, relates primarily to damage to susceptible crops planted the year following the herbicide application.

Herbicides can be expected to have a significant social impact. The requirement for hand labor has been reduced dramatically in many crops, such as sugar beets, peppermint, and onions. Although this could influence unemployment levels in some cases, labor available for hand weeding in those crops is in fact becoming scarce and very expensive. Reduced requirements for hand weeding may allow family members to have more time for more productive work activities. Of course, a major social effect of herbicide use has been the continued production of lower cost and higher quality food products for the American consumer.

The degree of weed control required for optimum economic return varies with the crop. In a few cases nearly complete weed control is required; for example, seed crops for certification must have few or no weeds whatsoever. This may require many methods in addition to herbicides, including hand-rogueing. In most crops, however, the additional cost required to control 100 percent of the weeds is seldom justified economically.

Minor Acreage Crops

Many vegetable, fruit, and agronomic crops are grown on limited acreages in the United States. The Agricultural Handbook (USDA, 1972) suggests controls for one or more weeds in 82 crops, 43 of which are vegetables and 14 of which are agronomic crops. In addition, suggestions are made for weed control in deciduous tree fruit and nut crops, small fruits (berries and grapes), citrus and subtropical fruits and nuts, and ornamental plantings. Weeds in these crops can cause serious reductions in yield and quality, with increased costs of production. To the individual grower the weed problems in these crops are equal in importance to those in major crops. While many of these crops may be grown on rather large acreages in specific localities, their production, both in terms of volume and from an economic standpoint, may render them as minor crops or minor uses.

The principles, practices, and need for weed control that apply to "major acreage crops" are generally applicable to "minor acreage crops." Herbicides generally have not been developed specifically for use on minor crops. Due to the cost of development, most chemical companies have felt that they cannot afford to produce a herbicide for the limited market involved in minor crops. Historically, a company that had acquired a label approval for a herbicide on a major crop could, at limited cost, extend the label to include other crops that had similar weed problems. As a result, growers have been able to use herbicides that were primarily developed for other crops and other cropping situations, even though the herbicides had not been developed specifically for their needs. With the current increase in total registration requirements, this is becoming more difficult. Because of the expensive tests required to obtain label approval for each crop, fewer herbicides will be available to the producer of minor crops, even though the crops may be valuable to a particular segment of our economy or may produce a specific type of food preferred by a portion of the population.

Growers of minor crops need to have the same alternatives available to them as growers of major crops. They need to be able to rotate herbicides and to integrate them into a total management procedure, just as other farmers do, to produce a crop profitably. Some viable procedure must be developed whereby the growers of minor crops may be assured of the continued development of improved herbicides needed in their management programs.

The term "minor crops" has been misleading. A newer term—"minor uses"—more clearly defines the problem. Now that registrations must be for specific weed-crop situations, a particular use where the volume of herbicide does not justify the cost of registration should be considered a minor use. This is true whether the weed-crop situation is in cotton (a large-volume crop) or watercress (a small-volume crop). All of the crops discussed in this report can be minor depending on the extent of the pest infestation.

The problem of registration for minor uses is further complicated and intensified by the expiration of patent protection, which lowers economic incentive for additional market development. There are a number of important herbicides for which patent protection has, or soon will, run out. Liability is another complicating factor since civil suit claims resulting from crop or ornamental damage can exceed profits from the sale of a small volume of herbicide.

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Row Crops

Principles, Practices, and Need for Weed Control.—In a nondramatic but very real way our survival and standard of living depend on successful crop production. Weed control is part of the more general problem of environmental manipulation, and thus can be considered in terms of ecological relationships. Such vegetation management consists of fostering beneficial and suppressing undesirable (inefficient or uneconomical) vegetation.

The modern system of producing food tends toward a system of monoculture. Although we attempt to grow row crops as monocultures, what we actually achieve are communities composed of crop plants and weeds. No one plant species, crop or otherwise, can fully exploit the resources of an agricultural habitat. In cropland and other disturbed areas numerous ecological niches are initially unfulfilled, creating enormous pressures for invasion by an aggressive species. The invasion is rarely entirely preventable, but it can usually be arrested in its early stages. Good husbandry seeks to maintain environmental conditions most favorable to the crop and least favorable to the weeds. This reduces the kind and number of ecological niches available for invasion by aggressive species. Economic demands in agriculture have forced farmers into greater specialization because they need to raise a crop with a higher net return per acre, and there are fewer machinery requirements in producing one crop rather than many. That such a system is feasible is shown by the hundreds of years of monoculture in Hawaii or many parts of the Mediterranean world. However, in such a situation greater care is needed to stay ahead of problems with pests and nutrient deficiencies.

Of the several factors that limit row-crop production, the control of weeds is one of the greatest. Only recently has research across the country produced data indicating that losses due to weeds were far more damaging than had been suspected. In the United States the number of weed species that commonly infest major crops is approximately 25 for peanuts, 30 for soybeans, 20 for corn, 15 for cotton, 30 for rice, 15 for potatoes, 40 for vegetable crops, and 50 for orchard crops. The scope of weed-control operations in field and horticultural crops is enormous. Between 1951 and 1960 American farmers spent more than $2.5 billion annually to control weeds. Although nonchemical weed-control methods are still the most widely used practices in crop production, improved herbicide technology has greatly increased crop-production efficiency. In recent years this technology, combined with efficient cultural practices, has resulted in an enormous reduction in the man-hours required to produce crops.

Losses.—Weeds cause damage in many ways. They may reduce crop yields and impair livestock production. They also increase production costs in growing and harvesting a crop and may impair the quality of agricultural products by contaminating them with noxious odors, seeds, or debris. Weeds are important in ecological or integrated pest-control programs because they may serve as important reservoirs of insect pests and their parasites and predators, as well as plant diseases and nematodes.

There is no reliable worldwide study, but it is evident that losses caused by weeds exceed the losses from any other category of agricultural pest. Losses due to reduced crop yield and quality and to the cost of weed control amount to 10 to 15 percent of the total value of agricultural and forest products. A few specific examples of losses due to weeds follow. Data in Alabama (Buchanan and Burns, 1970) show that mixed populations of annual grass weeds and broadleaf weeds could reduce yields by approximately 60 percent. When weeds were not removed until cotton reached the squaring stage, the growth pattern of the cotton was altered, maturity was delayed, and yields were reduced. In other studies maximum yields of cotton were produced when the crop was kept free of annual grasses and broadleaf weeds for approximately 8 weeks after emergence. However, even under such situations there is a concern for the presence of weeds in the harvested crop. Several investigators have noted that weed control by hand hoeing during early cotton growth results in lower yields than those obtained from plots treated with herbicides (Holstun, 1963 and McWhorter and Holstun, 1957). In addition, the quality of harvested lint cotton must be considered, because one large crabgrass plant per 6 meters of row is sufficient to reduce the grade of mechanically picked cotton (Garner *et al.*, 1958).

Shadbolt and Holm (1956) published data that can be used to estimate potential weed losses in vegetable crops. The data show that tremendous yield losses can occur when only a small number of weeds are left in a normal population during the early stages of crop growth. A weed stand only 15 percent of normal reduced carrot yields by 39 percent and onion yields by 48 percent; 30 percent of normal weed stand reduced the yields by 47 and 68 percent, respectively; and 50 percent of normal weed stand reduced the yields by 62 and 76 percent, respectively. In vegetable crops, weeds often reduce fruit set and fruit size. Fruit quality, including flavor, color, and texture, is also lowered. Maturation is irregular and harvesting is difficult when weeds are present. Danielson (1970) reported that annual losses due to weeds in plantings of vegetable legumes may be estimated at more than $110 million.

Some classic studies in the Corn Belt by Knake and others (Knake and Slife 1962, 1965, 1969) indicated that one foxtail weed plant per foot of soybean row reduced yields by 2 bushels per acre, with increasing stands causing greater yield decreases. Wilson and Cole (1966) found that morningglory reduced soybean yields, increased lodging, and increased harvesting problems.

Dawson (1965) reported that unchecked weed competition can eliminate sugar beets as an economic crop. Yield reduction of 94 percent due to weeds has been recorded under irrigated conditions. In Colorado, kochia or lambsquarter reduced sugar beet yields by more than 94 percent (Weatherspoon and Schweizer, 1969). Similar results have been reported in Wyoming and New York. These reductions indicate complete crop failure, since the smaller sugar beets could not be harvested on a practical basis because of the dense stand of weeds. The loss in sugar beet yield from weeds that escape the thinning operation or emerge after thinning can be costly. For example, Brickey (1965), reported that in California one weed per six sugar beet plants or 17 weeds per 100 feet of row resulted in yield reductions of 2 9 tons per acre.

Principles.—A basic principle of plant competition and weed control is that the *first* plant to occupy an area has an advantage over all later arrivals. This principle is of foremost consideration in practical weed control where cropping practices are always directed to the establishment of the crop ahead of the weed. Weeds that emerge after the crop is well established may not pose a serious problem, assuming that no ecological niches are exposed too long. In addition, competition between crops and weeds is usually most severe when the competing plants are most alike in vegetative habitats and demand on resources.

All crops grown on a farm are subject to weed competition. Most weed-control practices and techniques exploit biological differences between the crop and the weed that are accomplished by manipulating the shared habitat. Any attempt to put the crop in a dominant competitive position in the crop-weed association depends on the differential response of crop and weed to some factor of the habitat that can be modified or manipulated with predictable results. This basic concept underlies effective weed-control practices. However, the choice of methods and techniques of agricultural weed control may vary with the region, the crop, the nature of the weed, and the level of agricultural mechanization.

The degree of competition between weed and crop varies with the crop species. The weed problem for soybeans is different from that for corn, because weeds can shade soybeans but are less likely to shade corn once the plants become established. Although the shading effects of weeds on soybeans are most apparent when the weeds overtop the crop, recent studies show that velvetleaf plants significantly reduced growth and yield when placed on one side of the soybean rows even though they never grew taller than the bean (Burnside and Coleville, 1964). Side shading has been shown to be a significant factor in yield reduction. With vegetable crops, such as onions, beets, and carrots, shading by weeds can exert an almost overriding effect in many situations.

Another basic principle of row-crop weed control is to use control methods that are directed at weed survival mechanisms in the soil wherever possible. For annual weeds the objective is to prevent seed production and deplete plant food reserves. For perennials the destruction of underground vegetative organs is sought. Many soil-tillage and seedbed-preparation practices may minimize the competitive effects of weeds and crops. However, they may be largely ineffective in dealing with the basic survival mechanisms of a weed species.

There has recently been much publicity about the so-called green revolution with the new varieties of crops being produced. One thing frequently ignored is that, if these new miracle varieties are grown in the environment of the old varieties they are replacing, they often produce very little more yield. The most important feature of these new varieties is their capability to utilize efficiently fertilizers and irrigation and to produce well in dense plant populations. For this to occur the new varieties must be kept free of weeds that would otherwise use the fertilizer and water and perhaps smother the crop.

Methods of Control.—In contrast to other agricultural disciplines and their techniques, no method of weed control has ever been totally discarded. The oldest methods still have their place and are often combined with new procedures. Unlike insect and disease pests, weeds are relatively steady components of the agricultural environment and do not appear as periodic plagues exciting public clamor and support for action. There is a major basic difference between herbicides and other pesticides in their function as part of modern agriculture. Insecticides and fungicides protect crops and stored products from the direct attack of various pests. Herbicides not only protect growing crops from the heavily detrimental effects of unwanted plants but also offer the promise of weed-free crop production. This would make it possible to completely change the basic agricultural practices that have been carried on for centuries. Because weeds have always been associated with the production of crops and because the damage they cause is less obvious than that caused by other pests, there has often been a lack of a true appreciation of how damaging weeds are to efficient production. Once it is possible to create a weed-free environment cheaply and efficiently with modern agricultural procedures, many of the historical agricultural practices can be changed.

Nonchemical Weed Control.—The weed-control methods used in row crops are classed as preventive, biological, habitat management, physical, or chemical. *Preventive weed control* encompasses all measures taken to forestall the introduction and spread of weeds. Preventive measures may reduce infestation, but no preventive program can be expected to eliminate the numerous species of weeds found on any given land area. Because of the high reproductive capacity, special dissemination characteristics, dormancy, and high seed viability of weeds, preventive weed control is difficult if weeds are in, or adjacent to, the farmer's field. The effectiveness of a preventive program varies with the weed species. For example, because weeds like Canada thistle and kochia are readily spread by the wind, it is unlikely that preventive practices will effectively control them. Prevention of weed seed production, good farm-management practices (clean, vigorous, and well-adapted seeds), optimal rate and placement of fertilizer, timely tillage, crop rotation, use of clean farm equipment, animal management, and proper weed control on irrigation and drainage waters are some of the preventive weed-control methods currently being used.

The use of natural enemies to reduce the population of a plant species is known as *biological control.* When suitable and effective agents are available, this method is cheap and relatively permanent. The objective in biological control is never eradication; it is reduction of a weed plant density to economically acceptable levels. Biological control of row-crop weeds has been viewed conservatively for two reasons: (1) the possibility that it may not be as effective as other methods in obtaining an adequate degree of weed control and (2) conflict in the classification of a given plant as a weed, particularly since introduced agents may readily move from areas where the plant is a weed to areas where it is considered of value. Because of the risk to other plants, insects that are unspecialized feeders are not used in plant biological control. Many weeds are close relatives of crop species; examples are wild oats and cultivated oats, Sudan grass grown as forage and johnsongrass, and potatoes and tomatoes and the troublesome perennial weed horsenettle. Thus we are concerned with a relation where the introduced enemy is food limited and the weed host is enemy limited in a typical host-parasite interaction. By the very nature of the controlling mechanism the absolute impact of an enemy's action is automatically lessened as the density of the host declines. Also, many weeds are erratic in their occurrence in time and space, and the need for control may be urgent.

Although these factors lessen the likelihood of obtaining success with biological control, they do not preclude the possibility. The greatest disadvantage is that biological control is by its very nature a very selective and specific process. It cannot be used to control a complex of many weeds. It has striking utility where a single aggressive weed is devastatingly troublesome. However, the current usage of herbicides has shown that, if one specific weed species is eliminated or controlled in a given crop, other weed species are likely to invade and become the dominant weed problem. Thus any controlling factor that concentrates on one specific species is not likely to be the long-term solution to controlling weeds in any crop.

Some weed-control techniques manipulate the environment to reduce or eliminate competition by weeds or prevent their introduction or spread while the desired use of the environment is maintained. This procedure is known as *habitat management.* Weed species that may infest any given area are so numerous and diverse that any one control method is rarely satisfactory. Often, however, the interaction between weeds and their environment is delicate, and a change in the timing of events or condition of the environment may have an effect on the kind, stand, and vigor of weeds. For example, in the southern great plains region, winter small grains planted late in the fall do not have problems with cheat, but yields may be lower and cattle cannot fall graze on the forage. As crops are rotated, varying conditions of soil manipulation and planting procedures, tillage, fallow methods, mulching practices, and fertilizing practices may be used. Manipulation of water supply as it varies for different crops in the form of irrigation, flooding, or draining may help to control weeds as a habitat-management practice. Such variation makes it difficult for a single weed species to become a major problem in a specific area.

Physical methods are the oldest known procedure for controlling weeds and are still dominant in modern weed control. However, they cannot by themselves provide the degree of weed control needed in modern agriculture. Seed dormancy, the presence of various perennial underground storage organs, the production of literally thousands of seeds per weed plant, and the wide dissemination of seed by various means all combine to produce conditions under which many species cannot be completely controlled by physical methods.

Various physical control methods can be used, including tillage (physically altering the weed relationship with the soil), mowing and cutting, flooding or draining, the use of heat, and smothering. Of these procedures, tillage is probably the most widely used.

Tillage for weed control includes all soil-disturbing procedures ranging from hand pulling or hoeing through mechanical land preparation to machine cultivation of large acreages after the crops have emerged. Preplanting tillage (seedbed preparation) removes germinated weed seedlings but does not produce a significant depletion in seed reserves in the soil. Postplanting tillage (cultivation) may remove or bury weeds in the row, but it weakens crop plants through root pruning or other injuries. In general, cultivation is of little benefit other than for weed control under many soil conditions. However, in very heavy soils cultivation may offer benefits beyond weed control, particularly in aerating the soil and permitting greater moisture penetration. Thompson *et al.* (1931) found weed control to be the main advantage derived from one cultivation of vegetable crops. Later cultivation injured roots and actually reduced yield. Cates and Cox (1912) concluded from 125 tests in 28 states that cultivation benefited corn only by the removal of weeds. The frequency of tillage operations ranges from a single operation of a one-way disk and planter to repeated plowing, disking, and harrowing before planting and repeated cultivation after planting.

In general, tillage operations are effective primarily against seedling weeds. They are relatively ineffective against intact seed in the soil and against perennial weed species. With most perennials the main accomplishment is removal of the plant top without significant injury to the root storage organ. Adverse weather conditions severely limit the usefulness of many tillage operations. Furthermore, continued operation of heavy tillage implements over a field is very detrimental to soil conditions; procedures that can replace heavy tillage implements have been found to increase yield, improve soil structure, produce better soil aeration, and allow roots to permeate the upper layers of the soil more successfully. Yarrick (1946) indicated that the near elimination of tillage was an important innovation for the citrus industry.

The wide spacing of row crops is generally governed by the necessity of maneuvering between the crop rows to cultivate for weed control. The traditional 40-inch corn row was determined by the necessity of having a horse or mule walk between the rows while cultivating. With the introduction of modern weed-control methods, it is no longer necessary to maintain these spacings. Research is showing that the traditional wide rows can be reduced considerably, and higher crop-plant populations in the field can produce higher yields more economically and frequently with less need for pest control. If conditions are such that the crop seedlings can emerge and grow faster than competing weed seedlings, narrow-row plantings may be more productive than widely spaced rows, which leave sufficient space for competing species.

So-called minimum-tillage procedures are coming to the fore. These permit economically successful crop production while requiring less frequent soil disturbance for weed control. These procedures, however, must involve postplanting weed-control methods other than tillage.

Other physical control methods are generally less useful with cultivated row crops. Mowing and cutting are effective methods for perennial forage crops but cannot generally be used in cultivated crops. Draining is useful in certain specific areas, but it is not an operation that is used on a repeated basis. Flooding is used in some field crops but generally not for cultivated crops. Heat is a practical means of controlling weeds selectively in some cultivated crops. The use of flamers to control weeds in cotton has long been an established practice. Selective flaming has also had limited use in other crops, such as corn, soybeans, grain sorghum, and castorbeans. Weed kill is accomplished by moving an intense flame along the base of a weed-infested crop. Selectivity requires very careful timing and precise physical conditions, both of the soil and the crop. Flaming has definite limitations, but it can be used under certain situations. In most crops weed control cannot be obtained from flame alone; it must supplement other weed-control practices. Flaming requires propane (a petrochemical) as a fuel source.

Chemical Weed Control.—The other major method of controlling weeds in row crops is the use of herbicides. Herbicides can be used either to kill weeds or to inhibit their normal growth. Their means of accomplishing this are diverse and in some instances unknown.

Research with 2,4-D after World War II established that herbicides could be effective in very small quantities, highly selective, and systemic in action. The small quantities offered promise of inexpensive weed control. Selectivity meant that weeds could be killed in the presence of crop plants or seedlings. Systemic action made it possible to kill the underground parts of plants by applying herbicides to the foliage. Although its effectiveness was dramatic, it was soon found that 2,4-D was no panacea. Tolerant broadleaf weeds and resistant grasses survived treatment and increased in number. This led to the development of other herbicides in attempts to control these various weed species and to extend the usefulness of the herbicide procedures to other crops that may themselves be susceptible to 2,4-D. As time has passed, it has become evident that no single herbicide is sufficient and that our weed problems constantly change.

The farmer uses herbicides because his objective is to economically grow as much of a useful crop as possible. In modern agriculture he must attempt to channel the maximum amount of available resources into useful crop production of improved quality. Herbicides have played an important role in farmers' ability to increase crop production while withstanding the present cost-price squeeze and the decreasing farm-labor supply. In 1950, 75 man-hours were required to produce 1 acre of peanuts in Georgia; in 1969, only 15 man-hours were required. During the last 30 years the yield per acre has tripled for corn and potatoes and has approximately doubled for wheat, peanuts, and cotton (32). At the same time, the man-hours required to produce an acre of each of these crops decreased by 80, 36, 66, 77, and 70 percent, respectively. Chemical weed control contributed dramatically to this increase in productivity per man-hour expended.

Some of the major benefits of herbicide use on farms are the following:

1. The physical burden of weed control is diminished because much of the hand labor is eliminated.

2. Fewer people are involved in farm work where machines and herbicides are widely used; where fewer people are required to produce food, other vocations can be pursued and the general well-being of the entire population can be enhanced.

3. Increased productivity has resulted in efficient farm production at a lower price per unit.

Herbicides may be applied to weeds in crop rows where cultivation would be impossible. Also, preemergence herbicide treatments provide early season weed control and prevent weed competition long before tillage methods would be used to control the weeds without crop injury. Weed competition during the early stages of crop growth is responsible for the greatest loss in yield. Cultivation often injures the crop root system as well as the foliage, and selective herbicides reduce the need for cultivation. Herbicides also reduce the destructive effects of tillage on soil structure. Moreover, preemergence treatments can be controlling weeds even if the farmer cannot get into the field to cultivate due to rainfall or other adverse conditions. Chemical weeding permits simplification of crop rotation, avoidance of soil disturbance, adjustment of row spacing to that optimum for each crop, and economy of labor.

There are detrimental as well as beneficial effects from the use of herbicides. Possible detrimental effects of herbicides in cultivated crops could be summarized as (1) drift from the target area and detrimental effects to nontarget plants, (2) persistence in soil, (3) injury to treated crops, (4) potential persistence in air and water, (5) movement in groundwater, (6) undesirable shifts in the weed population, (7) hazards to animals, and (8) hazards to man. The major herbicide problems have generally been due to herbicide drift to nontarget species or persistence in soil and water.

Although herbicides are necessary for future crop production, their undesirable secondary effects cannot be ignored. As a group the organic herbicides are primarily toxic to green plants. Most of them are not highly toxic to members of the animal kingdom (WSSA, 1974; Hayes, 1964; Hayes and Perkle, 1966). The principal hazard in the use of herbicides is to crops or other desirable vegetation. The Governor's Scientific Advisory Panel on the use of agricultural chemicals in Texas (Adkisson, 1970) indicated that the "principal danger from herbicide pollution is to crops and plant life rather than to man or wildlife. This pollution can be reduced through proper application or by the use of mixtures of nonpersistent herbicides." Although the principal hazard is to desirable vegetation, the entire biological environment must always be considered.

Type. Herbicides can be classified as either inorganic or organic. Inorganic herbicides are not widely used as selective herbicides in row crops. Many different types of organic herbicides are being used, and they can be roughly classified into various chemical groupings. Herbicides within a given chemical group may be somewhat similar in the type of weeds controlled, the type of crops in which they are selective, and their mode of action. However, there may be wide variation in the specific weed species that will be susceptible to any given member of a chemical family. Also, there can be a variation in the crops susceptible to different chemicals in the given family. Linuron, a substituted urea herbicide, can be safely used in soybeans; fluometuron, also a substituted urea herbicide, will kill the crop. Atrazine can be safely used in corn but will kill cotton; with prometryne, another triazine herbicide, the reverse is true. Trifluralin provides excellent control of crabgrass in soybeans, peanuts, and cotton but little or no control of morningglory or cocklebur.

Chemically there are wide differences among the various herbicide families. No specific chemical structure is universally successful as a herbicide, and no portion of a molecule can be pointed to as the active agent. Although some major herbicide families find more use in cultivated crops than others (e.g., the triazines, the substituted ureas, and the dinitroanilines), some members of every chemical family are used in one or another cultivated crop.

No attempt has been made in this report to discuss specific chemical weed-control procedures used in dozens of row crops with more than 100 selective herbicides. A given herbicide is quite specific as to the crop it is used in, the time of use, the weed species controlled, the prevalent soil conditions, and the environmental conditions before and after treatment. Recent publications by the National Academy of Sciences (1968) and the Food and Agriculture Organization (1970) summarize current herbicide procedures.

Knowledge of the environmental factors regulating herbicide performance or limiting herbicide usage is essential to the successful control of weeds with herbicides. The risk of failure is always present. Environmental factors appreciably modify plant growth and plant response to imposed conditions. Thus variation in environmental factors will have a significant effect on herbicide action. The same response might be expected time after time from a typical herbicide applied at the same dosage rate in the same environment. In another environment the rate required for a similar level of activity may differ by two to four orders of magnitude. Various properties of soil and herbicide, as well as environmental factors, influence activity and persistence through their effect on volatilization, movement in soils, microbial decomposition, adsorption to soil colloids, plant absorption, and plant metabolism. Frequently, the limitations imposed by the environment on the weed control obtained with a specific herbicide may be overcome by using a different herbicide. Often the advantage of adding a new herbicide to the arsenal of those available is that it covers a specific environmental or weed condition not presently adequately covered.

Most growers have come to realize that adequate and economical crop production does not mean that all weeds must be eradicated from a field. The weed population must be reduced to a level that is relatively noncompetitive with the crop. If given an advantage, the crop can frequently outcompete the weeds in the same field and produce an economical yield. Some crops are more effective in this way than others. A crop like peanuts or soybeans, which produce a dense, shading type of growth, will prevent the emergence of many weeds once it has established a sufficiently dense foliage. Crops like tomatoes or sorghum do not produce such dense foliage early in the season, and thus there may be trouble with weeds later in the growing year. Thus the degree of control needed will vary with the crop and will influence the choice of herbicide.

Although there are variations in the degree of weed control needed in various crops, the risk of failure is always present. Unfortunately, this sometimes induces the farmer to use more herbicide than may actually be needed. Chemical weed control in the 1940s was used in conjunction with various other procedures strictly as an added weed-control method. If the herbicide was not successful, the farmer could always plan to cultivate his crop until midseason. Since then the economic situation has imposed on the farmer the need to reduce costs while increasing production, and the farmer has been forced to improve production procedures. These improved procedures frequently include the use of herbicides in situations where no other weed-control procedure can be economically used. Examples of this include the narrow-row growing of sorghum in irrigated areas of the southwest as well as the production of minimum- or zero-tillage crops in the Eastern United States. Under these situations the failure of a herbicide treatment or the absence of alternative herbicide treatments can readily mean complete loss of the crop. Therefore, under such situations the risk of failure is a major consideration to the grower in establishing his herbicide program.

Although the elimination of early competition to the crop permits the plants to reach their fullest yield, there are also hazards to a failure in weed control late in the growing season. Modern harvesting machinery has been developed to harvest clean crops. The presence of a heavy weed stand at the time of harvest hinders or makes impossible the use of harvesting machinery. The presence of excessive grasses in cotton causes a discoloration of the lint that cannot be removed and therefore reduces the quality of the cotton. The presence of excessive pigweed in a soybean field can completely prevent combine operation or slow it down sufficiently to drastically increase the cost of harvesting. Often the only possible control procedure for a weed problem appearing in a maturing crop is the use of herbicides.

Persistence. The detoxication, degradation, and disappearance of herbicides used in cultivated crops vary widely among the soils and in response to differences in environmental factors. The residues of some herbicides used in cultivated crops may persist from one season to the next and injure sensitive crops the season after application. However, this is more detrimental to the farmer growing crops on that land than to anyone else. Current research is finding herbicides that are less persistent and do not have a 6- to 12-month carryover in the soil. However, some persistence is an essential feature of some herbicides. A herbicide like trifluralin, which is applied in April prior to the planting of a cotton or peanut crop in May, must have some persistence if weeds are to be controlled until the crop has developed enough to fend for itself. Frequently, a 2- to 3-month period of persistence is optimal. The development of more and better contact herbicides can to some degree reduce the use of persistent materials, but these compounds will never be able to completely replace the persistent herbicides. Ideally the herbicides should control the weeds until they are no longer a problem in the crop and then degrade.

Several years ago there was considerable concern about the potential accumulation of high concentrations of herbicides in the soil of cultivated crops due to repeated application of herbicides. Evidence from many long-term experiments indicates that the accumulation of high concentrations does not occur. Repeated annual applications at selective rates to the soil does not tend to build up into an accumulation that will injure the crops being grown (Hill *et. al.*, 1955; Burnside *et. al.*, 1969; Gunther, 1970).

Systems of Weed Control. Research has shown that agricultural crop production can be increased without an increase in environmental contamination by adopting the systems approach to weed control in cultivated crops. This is not a new concept. Weeds have always been controlled best by a variety of practices, and man for thousands of years has employed combinations of tillage, cropping, and environmental management in his battle against weeds. The twentieth century revolution in weed technology has permitted application of the systems concept. Weeds may now be dealt with systematically over time and space through a series of coordinated techniques that have a greater impact than any one component by itself. Therefore, deleting any one component of the system is much more serious than just omitting one step in a practice. The primary goal of any weed-management system is to maintain an environment that is as selectively detrimental to weeds as possible.

Though the successful employment of specific or combined ecological, cultural, mechanical, biological, and herbicidal methods approaches the objective in controlling a particular weed species, the weed complex may change as the environment changes or resistant strains become prevalent. Fortunately, more is continually being learned about weed control, and new treatments are constantly being perfected. These developments serve to improve existing weed-management systems and suggest changes in approach for methods that become ineffective or obsolete.

Currently there is considerable interest in the zero- or minimum-tillage crop-production system, and this has found expression in changes in our weed-control procedures. In such programs a herbicide is doing more than just controlling weeds. Herbicides are also crop production tools. They are tools without which a system of minimum tillage would not be practicable. The many advantages of minimum-tillage procedures include major reductions in soil compaction, soil erosion from wind and water, and production costs. Minimum tillage is one pest-control system that would not be possible without pesticides.

Weeds compete with cultivated crops throughout the growing season. Usually no one herbicide will give full-season control of most broadleaf weeds and grasses. Different species of weeds often compete with a crop as the season progresses. Thus, to obtain full-season weed control with or without cultivation, it is frequently necessary to use different herbicides at different times. The grower must select herbicides best suited to the particular weed problem. This is particularly true as only the less persistent herbicides are produced. If most of the herbicides are short-lived, the grower may have to apply herbicides several times during the growing season to obtain full-season weed control.

Complex systems will not control all weed species under all conditions, but the chances of failure can be greatly reduced. The complementary action of components in a weed-control system is apparent in a study conducted of cotton (McWhorter *et. al.*, 1956; Holstun *et. al.*, 1960). Flame weeding reduced hoe labor requirements by 11 hr/acre, and a preemergence herbicide reduced them by 18 hr/acre. These individually total 29 hr/acre, but the actual reduction where both procedures were used was 47 hr/acre. In Nebraska weeds reduced grain sorghum yields by about 33 percent where either cultural or chemical practices were used alone for weed control. Plots that received both herbicides and cultural weed-control practices produced 1000 lb/acre more grain than plots receiving either control treatment alone (Burnside *et al.*, 1964).

Alternatives. Although the common weeds of field and pasture are taxonomically diverse, they are all nuisances. They are particularly adapted to thrive in close association with man and his domesticated plants and animals. Hence the use of any one procedure can only rarely provide the degree of weed control needed for economical crop production. Different alternative methods of weed control must always be considered, and more than one alternative is needed.

Tillage or soil-disturbance operations provide acceptable alternatives to the use of herbicides for weed control in some situations. However, as has already been shown, there are many problems that tillage cannot solve because of environmental conditions or the characteristics of the weed species to be controlled. Often, if the farmer planned to cultivate, it may rain enough to prevent cultivation. By the time this occurs he may have lost his best possible alternative herbicide treatment.

One possible alternative to the continued use of a dominant herbicide is to practice herbicide rotation, either in conjunction with continuous cropping of a single crop species or in conjunction with a crop-rotation procedure. At the University of Illinois F. W. Slife (data to be published in *Weed Science*, 1975) has now completed 6 years of a field experiment involving rotations (or the lack thereof) of crops and of herbicides. Continuous corn and continuous soybean plots consistently provided better yields in plots that received either a main or a rotation herbicide as compared to those that received only tillage for weed control. The same was true to a lesser degree of corn or soybeans in rotations. Evaluations of weed seed in soil at the beginning of the experiment and after 6 years of treatment showed that there was a weed-seed buildup of selected species when a single main herbicide was used each year under a continuous corn rotation. The same was true even to a greater degree under the nonchemical treatments. With the rotation of herbicides (using a different herbicide treatment each year in the corn crop), the weed-seed population in the soil was drastically reduced. With continuous soybeans the weed-seed population of the soil dropped with both the main herbicides and the rotation herbicide procedures but increased threefold under the check conditions. The continuous wheat treatment showed a seed increase in the soil regardless of the herbicide used. Under rotation conditions the changes were less drastic, but in general weed-seed populations increased under the nonchemical conditions and either maintained a relatively stable level or decreased under the herbicide treatments. This provides an outstanding example of why a diversity of herbicides is needed for any one particular crop. The use of herbicide rotations or alternative herbicides can also contribute to a lessening of potential environmental contamination due to the continual variation in chemical structures being used on a given site. Thus there is less chance of an accumulation of a herbicide or of off-type organisms or wildlife becoming adapted to a specific structure.

The importance of weed control as a major element of integrated pest control in agricultural crops has been frequently overlooked. Integrated control involves a program of pest control that utilizes all the control means to the best possible degree. Unfortunately, many feel that these involve only insect-control procedures. They should include cultural practices that minimize the potential for the pest or enhance the ease of control—such as favoring natural predators, use of favorite plant species as trap crops, and the elimination of weeds that act as breeding grounds where insects or diseases increase and later invade the developing crop. Integrated pest controls should therefore control all types of pests in the field, not just insects.

The use of herbicides for weed control, however, does not eliminate the need for sound cultural practices, preventive methods of weed control, and good management. Most weeds in cultivated crops are still controlled by nonchemical methods, that is, mechanical, cultural, and biological. Weed control with herbicides places a premium on the careful integration of weed-control methods with all other cropping practices. The most dependable results in weed control are currently achieved by using as many of the various methods of weed control as feasible in any given situation. Today's farmer does not have many alternatives that exclude herbicides in an integrated weed program. He must produce as efficiently as possible or go out of business. The trend of increasing farm size and decreasing labor supply has left the agricultural producer more and more dependent on herbicides. The available alternatives, at least those that are currently feasible and economical, are already being used to a great extent in integrated weed-control programs.

Major steps in the reduction of the total amount of herbicides used per given unit area are becoming more and more possible through various types of research into factors influencing the activity of herbicides. Changes in herbicide formulations, methods of applying the herbicide, minimum effective dose studies, etc., tend to reduce to the greatest extent possible the amount of herbicide being applied to any given area.

Shifts. The use of herbicides or any intensive weed-control practice to control a specific group of weed species has caused changes in species composition. The common herbicide 2,4-D reduces annual broadleaf weeds, so that annual grasses tend to increase in population and density. The use of trifluralin for many years to control annual grass weed species in southern broadleaf crops has resulted in a definable increase in the population of resistant broadleaf weed species. Such weed-population changes have occurred all over the country and are continuing. There is no reason to expect this problem to decrease as long as a standard herbicide is widely used in a specific crop. The most effective way of economically attacking such ecological shifts is through the use of alternative practices and alternative herbicides. However, herbicide rotation requires the availability of several herbicides for a specific crop in a specific area of the country. The herbicides that can be used in soybeans in the Corn Belt or Eastern United States are quite different from those that would do an acceptable job of weed control in soybeans in the Mississippi Delta. Sorghum herbicides available for the northern Great Plains cannot be used safely in sorghum grown in the southern

Great Plains. Thus farmers need a greater arsenal of herbicides for use in cultivated crops, at a time when the list of available herbicides is decreasing. To produce crops economically without undue environmental contamination, the grower must have flexibility in chemical usage. New and safer methods of testing and using herbicides will ensure hitting the target with a minimum effective dose and the least likelihood of environmental contamination. It appears probable that with adequate research additional herbicides will be discovered for specific uses that will prove safer to the applicator, the consumer, and the environment than those now available.

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Fruit and Nut Crops

General Principles and Practices.—Orchards produce fruits such as apples, pears, prunes, and oranges, and nuts such as walnuts and almonds. Small fruits include fruits such as grapes, strawberries, cranberries, and raspberries. The culture of these fruits is widely distributed throughout the United States, with about 11 million tons of fruit, excluding citrus produced in 43 states each year (Lange, 1970). Weed control in fruit and nut crops is a problem of considerable proportions. Weeds in deciduous fruit trees in California alone are estimated to cost the growers approximately $36 million per year, half of which is for weed-control programs and the other half is from losses due to weeds (Lange, 1968). In California citrus crops, total costs of both control measures and weed losses were estimated to be $23 million in 1964 (California, 1964). Weeds compete with trees and vines for water, nutrients, and, in young plants, light. They facilitate attack from rodents, insects, and pathogens. They interfere with management operations. They may reduce yield and quality of the crop. In some cases they may conceal poisonous snakes, which quite obviously interfere with harvest operations.

The establishment of orchards represents a major investment. The average time for orchards to be commercially self-sustaining ranges from 4 to 5 years for peaches and plums to 9 to 10 years for apples and walnuts (Lange, 1970). All the fruit and nut trees under discussion are perennial. Some plantings are kept bare continuously; in others, areas between the tree rows are planted with perennial sod or an annual cover crop. These plantings may help to prevent erosion and aid in water penetration.

Methods of Control.—Common methods of weed control in the United States are tillage or mowing, often in combination with herbicides. Flaming is sometimes used. Tillage is easy, equipment is readily available, and timing is often flexible. Annuals are easily controlled, and perennials can be controlled through carbohydrate starvation by repeated operations. However, repeated tillage operations can cause soil compaction and create plow soles or impervious layers beneath the surface layer. Mowing is fast and cheap and helps to maintain vegetation for erosion control. It is ineffective close to the trees, however, and on prostrate-type weeds. Vegetation that can compete with the crop is still present. Flaming or burning is relatively cheap and easy, but repeated treatments (up to 20) are needed to control perennial weeds. There is also a danger of injury to the crop.

Grazing animals can be used among large trees, but they often injure small trees and shrubs. In addition, they are difficult to manage, and unpalatable weeds may become predominant. Hand labor offers one possibility of control adjacent to the base of the trees, but the cost of hand labor has become almost prohibitive on a commercial scale.

The use of herbicides in orchards and on berry farms has increased dramatically. Herbicide use on fruit and nut trees increased from an estimated 5000 acres in 1959 to 267,000 acres in 1962 (Shaw, 1964). It has been estimated that over 500,000 acres were treated in 1965 (USDA, 1968). This increase in use has continued since.

Herbicides are usually applied in 4- to 6-foot strips along the tree rows, with mowing or tillage used in the middle. This results in a 50-percent reduction in mowing or tillage operations in orchards because it eliminates the need for the mechanical operation to be carried out in two directions. Complete herbicide coverage is sometimes used, particularly if basin or furrow irrigation is utilized.

Herbicide use, as indicated by its rapidly increasing popularity, offers some definite advantages. Increased tree growth and increased yields have been demonstrated with chemical weed control as compared with clean cultivation or sod culture. These increases are especially dramatic during the early stages of crop establishment and commercial production. In one experiment, for example, Leyden (1969) showed that yields of grapefruit in 1966 and 1967 were 95 and 107 kilograms per tree for complete chemical control, 10 and 74 kilograms per tree for clean culture, and 4 and 13 kilograms for sod culture, respectively. The trees had been planted in 1960. Soil compaction is reduced when mechanical cultivation is eliminated. Conversion from mechanical weed control alone to a combination using herbicides reduces root and trunk damage from equipment, eliminates weed competition, and generally results in a more healthy crop (Jordan and Day, 1970).

Air and soil temperatures seem to be higher in orchards under chemical weed control than under clean cultivation or sod culture. Less freeze injury and more rapid recovery have been noted in herbicide-treated orchards (Leyden, 1969).

A variety of herbicides are used in orchards and on small fruit. Repeated applications of weed oil and, more recently, paraquat are used as quick-acting contact materials. These materials have no soil activity. Their selectivity is based on avoiding contact with the foliage of the crop. Several soil-active compounds have been introduced for fruit and nut trees, including diuron, simazine, trifluralin, dichlobenil, and terbacil. Selectivity in these materials depends on the difference between the crop and the weeds in depth of rooting. These herbicides tend to remain in the upper layers of the soil and eliminate shallow-rooting weeds but do not contact crop roots in sufficient concentrations to cause damage. For this reason, complete dependence on soil-active herbicides can result in an increase in deep-rooted perennial weeds like field bindweed, Canada thistle, and johnsongrass. Furthermore, each herbicide is ineffective on certain annual weeds, so that repeated use of the same herbicide can convert the crop area into a solid stand of the resistant weed. In addition, resistant strains within a species may survive, resulting in a highly resistant population over a period of time (Ryan, 1970). Therefore alternating among various herbicides is generally a recommended practice.

Some foliage-applied, translocated herbicides are also used, including 2,4-D and dalapon. The compound 2,4-D is toxic to most fruit and nut trees if it contacts the foliage. Only nonvolatile formulations must be used, and shields are often used to prevent spray drift onto the leaves.

Herbicides are nearly always applied by ground sprayers in fruit and nut orchards, so spray drift is a minimal problem. Because the crop itself is sensitive to many of the chemicals used if contact is made with roots and foliage, nonvolatile foliage herbicides or soil-active compounds that do not move readily in the soil are used. Minor amounts of herbicides could possibly move out of treated areas with irrigation water or through sheet erosion. As weed oils are known to evaporate, large-scale usage could contribute to air pollution.

The efficacy of several herbicides used in perennial crops depends directly on their persistence. Unlike the situation with many annual crops, where persistence beyond the growing season is a disadvantage, extended soil life may be a distinct benefit in perennial crops, where rotation is not a factor. Such compounds as diuron, simazine, and terbacil may last from 1 to 2 years in the soil. However, because these herbicides are relatively immobile in the soil, adverse environmental effects are not probable.

Use of Alternatives.—Nonchemical methods of weed control are still feasible in fruit and nut orchards, but total dependence on these methods is not practical in many situations. The elimination of weeds from around the base of trees and vines is necessary, but it is very difficult by mechanical means. Damage to trunks and roots, soil compaction, and reduced yields are common results from mechanical weed control. Hand labor is becoming too expensive for economical production. Biological control by grazing animals is a possibility, but it introduces a series of management problems (predators, water supply, contamination of crop by manure, etc.) (Jordan and Day, 1970; Lange, 1970). A combination of chemical and nonchemical methods seems to offer the more practical approach in most situations.

Need for Herbicides.—Herbicides provide the most efficient and economical method of weed control in many orchard and small fruit crops. Where chemicals have been used, orchards are warmer, trees are more vigorous, and yields are higher (Jordan and Day, 1970). A choice of herbicides is necessary because of the variety of crops, weed species, and cultural and environmental situations in which crops are grown. Rotation of herbicides is desirable to prevent a buildup of strains or species resistant to one herbicide. With an ever-increasing cost-price squeeze facing agricultural producers, it is essential that such beneficial tools as herbicides continue to be available.

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Solid-Seeded Annual Crops

General Principles and Practices.—Solid-seeded annual crops include small grains (rice, wheat, barley, oats, and rye) and flax. In the future, this category may include many other crops (e.g., corn and beans) now grown in rows because of the need for cultivation and because of planting and harvesting operations. In some areas, herbicidal weed control and the development of new harvesting equipment have made it possible to grow snap beans in solid stands.

In the United States rice is grown primarily in the South and in California. Most other small grains are grown widely throughout the country. Upland cereals are drilled in 7- to 14-inch rows. Most of the rice in this country is grown in diked paddies and flooded. It may be drilled, seeded into the water from the air, or transplanted.

The number of weed species that commonly infest rice has been estimated to be at least 30 and, for other small grains, 35 (NAS, 1968, p. 254). Weeds appearing in rice may be aquatic as well as terrestrial in nature. These weeds can be extremely competitive. In the Pacific Northwest, grass weeds like annual ryegrass have reduced wheat yields from 75 bushels per acre in the best control treatments down to 2 bushels per acre in the weedy plots (Aldridge, 1971).

Upland small grains include both fall- and spring-sown types. Weeds found in winter grains are primarily winter annual weeds or weeds that germinate in early spring; those infesting spring grains are largely early-maturing summer annuals and perennials.

Methods of Control.—In a solid-seeded annual crop the possibilities of nonchemical control are limited. No successful biological agents have been introduced to date. However, various farming techniques contribute to reduced weed populations and should be considered in management systems. Dry fallowing to control perennial weeds and the use of weed-free seed can help establish clean crop stands. Shallow tillage after planting (blind tillage) can sometimes be used to control weeds that germinate faster than the crop, but this technique is limited in value since most weeds germinate over an extended period. Crop rotations can interrupt the life cycle of troublesome weeds and reduce their population. An example is downy brome in wheat, which can be held to manageable levels in the Great Plains by rotating infested fields to a spring-seeded row crop, such as grain sorghum, for 1 to 2 years. Weeds may be encouraged to germinate, then be eliminated with shallow tillage prior to planting. This can be helpful, particularly if the major weed species tends to germinate all at once.

In rice, water management is a critical factor influencing levels of weed infestation and determining the species present. Flooding to a depth of 4 to 8 inches helps control barnyardgrass seedlings, but may cause an increase in aquatic weeds. Timely drainage can reduce some weeds such as algae (Smith and Shaw, 1966).

Herbicides are becoming more widely used in all small grains. In 1966, 80 percent of U.S. rice acreage was treated with propanil and 50 percent was treated with phenoxy herbicides (Smith, 1967). The percentage of wheat and other small grains treated with herbicides is considerably less than that of rice, with approximately 35 percent of wheat acreage treated (USDA, 1966). Until recently, major herbicides used in small grains and flax were for broadleaf control. After the mid-1940s, 2,4-D and other phenoxy herbicides were widely used in the solid-seeded annual crops. However, improvement in the control of broadleaves was accompanied by an increase in 2,4-D-resistant broadleaves (e.g., wild buckwheat, blue mustard, and knotweed) and an increase in resistant grass weeds. Wild oats, annual bromes, annual ryegrass, green foxtail, and other grasses became more severe in upland grains, while such grasses as barnyardgrass and sprangletop increased in rice. New, short-strawed varieties of grains have been introduced. These high-yielding grains can profit from increased fertility levels without lodging, but their shorter stature causes them to be less competitive to weeds. Also, the increased levels of nitrogen and phosphorus required for optimum crop production may also stimulate the growth of grass weeds (Appleby, 1971; Smith, 1967). All of these changes have increased the need for new herbicides.

Several new herbicides have been introduced that are effective against weeds not controlled by 2,4-D and other phenoxys. Barban, diallate, and triallate are used for wild oat control in grains and flax. Diuron is used in the Pacific Northwest for the control of annual ryegrass in winter wheat and barley. Propanil and molinate are grass killers for rice. Bromoxynil, linuron, terbutryn, and dicamba have been registered for use in wheatfields primarily against 2,4-D-resistant broadleaf weeds.

Somewhat less than complete weed control is required in most grains. A few weeds can generally be tolerated without severe reduction in yields. However, some weeds (e.g., annual ryegrass and wild oats) become quite competitive, and even sparse stands can reduce yields. Other weeds, such as sunflower, may interfere with harvest operations. Also, incomplete control may contribute to increased weed-seed populations in the soil.

As with most herbicide treatments, the degree of success of herbicide applications in grains is varied. In general, 2,4-D has been fairly consistent for adequate control of susceptible weeds. The performance of newer herbicides, particularly that of soil-applied ones, has been less consistent.

Nearly all herbicides used in solid-seeded annual crops are reasonably short-lived in the environment, most of them having a soil life during the growing season of 8 weeks or less (WSSA, 1970). A few herbicides for grain crops are included in chemical families generally considered to have significant persistence; examples are diuron (phenylurea) and terbutryn (triazine). However, recommended rates are low because the selectivity of grains to these compounds is limited, and, at low rates, such materials have not caused injury to subsequent crops. In one study, runoff water from fields in the Willamette Valley of Oregon was analyzed for the presence of herbicides. Although large amounts of herbicides are used in the Willamette Valley in small grains, orchards, grass-seed crops, and others, no residues were found (Brannock, 1967), indicating that movement of phenylureas and triazines in the water is not a significant factor when used at low rates in cropland.

Probably the major undesirable effect from herbicides for grain crops has been spray drift onto nontarget areas. Drift injury from 2,4-D, mostly from aerial applications, is common throughout the United States. Propanil applications to rice in California have resulted in considerable injury to prune trees. The use of alternative herbicides has reduced drift injury significantly; an example is the use of bromoxynil, terbutryn, and linuron in the Pacific Northwest in areas surrounding vegetable and fruit crops. Continued development of new application methods, such as foam, spray thickeners, and improved design and placement of nozzles, will also reduce the spray-drift problem.

Use of Alternatives.—The use of herbicides in cropland should never replace good farming practices. As already mentioned, several nonchemical practices can help reduce weed populations. Such alternative practices should always be seriously considered and used when practical. Many situations, however, make the use of some techniques inappropriate. Most noxious weeds germinate *after* the crop has been planted and is emerging. This eliminates delayed tillage and blind tillage as feasible practices. Cultivation in solid-seeded crops is of questionable use, particularly in areas where fall-planted fields are wet or frozen in the winter. Hand removal of weeds is economically impractical in the extensive plantings of low-value crops. Crop rotations may be helpful at times, but in some areas rolling hills and low rainfall prevent the production of alternative crops.

Need for Herbicides.—If herbicides become unavailable for use in solid-seeded annual crops, the impact could be serious, especially in rice and in small grains in certain areas. The severe competition from weeds coupled with the lack of feasible alternatives in many cases would eliminate production of small grains from much of the Pacific Northwest and parts of the Northern and Northeastern States. Herbicides are used less extensively in small grains in the Great Plains. The need for several different herbicides has become more apparent as species and strains resistant to specific herbicides have increased. The wide diversity of environmental conditions, cultural practices, and weed species has already been pointed out, emphasizing the need for flexibility and diversity of tools available.

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Solid-Seeded Perennial Crops

The solid-seeded perennial crops of the United States are primarily improved hay and pasture species. Such croplands generally receive more management than native pastures and ranges and are periodically reseeded due to disappearance of the desired high-yielding and high-quality introduced species. As time passes after the introduction of the desired species, there is frequently a slow reduction in the population of the desired species and an increase in the population of the better adapted weed species. Most of the weed species are either nonutilizable as forage or have much lower protein or other quality factors. Trends toward dominance by weeds can be slowed or changed by judicious use of mechanical and chemical weed-control methods as well as by management procedures. Due to the wide variation in species used across the country and to climatic and soil variations, no one chemical or management practice is uniformly used. Nevertheless, many of these perennial crops can be maintained at a high productive level by present management techniques, which usually include some form of chemical weed control.

A major problem in such perennial crops is that perennial weeds are often favored by the same management practices that favor the crops.

Careful consideration must be given to selecting the control methods that are most effective for a particular pasture or hay crop and its specific environmental conditions. A management approach satisfactory in one situation may not work well in another. One management practice that must always be considered is the time or frequency of harvesting, whether by mechanical means or by livestock. Incorrect harvesting intervals can rapidly lead to the depletion of the carbohydrate reserves in the forage plants, with a consequent rapid deterioration in the quality of the perennial crop. Few mechanical control procedures are available for use in these solid-seeded perennial forage crops. Any procedure that would stir the soil would dislodge the desired crop as well as any weeds. Judicious cutting of weed seed heads can prevent some seed production, but it may also inhibit the development of the crop species. Such methods also have little effect on the control of perennial weeds. Liming and fertilization are often effective in encouraging the crop plant in the competitive struggle with invading weed species. However, some weed species are also favored by fertilization and thus become greater problems on the more fertile soil.

Solid-seeded perennial crops, such as alfalfa or legume grass mixtures, are particularly vulnerable to weed competition during their seedling stages. Almost invariably the crop germinates and grows slowly, thus providing the opportunity for rapidly developing weeds to overtop and severely shade them. In one study in Indiana, broadleaf weed seedlings were found to grow five times more rapidly than the legume seedlings (Klingman, 1970). In the past, growers have frequently planted a companion crop of cereal grains or other crops in an effort to reduce weeds in spring-seeded forage crops. However, research in many northern and northeastern states has shown that companion crops (e.g., barley and oats) may injure slow-growing forage species as much as do weeds (Klingman, 1970). Some planting or other management practices have been developed that favor rapid germination and growth of legumes to assist them in competing with weeds. Band seeding, crop rotations that reduce the prevalence of weed seeds in the soil, thorough seedbed preparation, mowing, and the use of herbicides are all practices that have been developed to help forage seedlings in becoming established. Each method involves the integration and use of certain weed-control principles and practices.

The time of planting of the forage crop has a major influence on the weed species to be found in it. Spring-planted crops frequently have problems with summer annual weeds like pigweed, smartweed, mustard, and foxtail. Late-spring plantings have a different set of weed problems. Late-summer or fall seeding probably causes the presence of winter annuals and biennial weeds, which characteristically start their growth at the onset of cool temperatures. Some of these are chickweed, henbit, wild mustard, pepperweed, and yellow rocket and cheat.

Herbicides are a major management tool in the establishment and culture of solid-seeded perennial crop species. Here again, a variety of herbicides are needed or used to fit a variety of environmental conditions and prevalent weed species. The development of herbicides that selectively kill weeds with minimal injury to forage legumes has caused some shift from seeding with a companion crop to seeding the desired species alone. In recent years the development of preplant herbicides to be applied before the planting of a forage crop has led to a major change in seeding procedures in some areas. Application of EPTC or Benefin and their immediate incorporation into the soil before planting controls many annual grasses (Muzik, 1970). However, both of these compounds are relatively expensive in relation to the value of the crop being produced.

More frequently, chemical weed control in solid-seeded perennial crops involves the use of postemergence treatments. This is particularly true when the forage crops can be seeded in the fall rather than in the spring. Most forage legumes (including alfalfa) can tolerate 2,4-DB, CIPC, dinoseb, dalapon, or other herbicides that can control winter annual weed species. The use of herbicides in "stale seedbeds" is another means of controlling weeds in new seedings. This involves preparing the seedbed several months before planting the desired crop. Some time before seeding, the weeds that germinate are killed with herbicides that do not persist long enough in the soil to interfere with the development of the young forage-crop seedlings. Since the soil is not disturbed by tillage, new weed seeds are not brought to the surface, and a lengthy relatively weed-free period may be available for establishment of the forage seedlings.

Legumes grown for hay compete with most weeds as long as the stands remain dense and the plants are vigorous. However, when the forage crop is dormant, it is less able to compete with winter annual weeds. Selective control of annual grasses and perennial weeds cannot be successfully accomplished at present. Preventive measures and mowing control broadleaf weeds but often increase the problem of weed grasses. Thus alternative procedures for weed control that might be developed will frequently result in a lessening of the crop stand, which results in increased competition from weeds. Once stands begin to weaken, a rapid invasion of weed species occurs.

Seed production in crops like alfalfa requires lower plant populations than are needed for hay production. Consequently, seed crops often provide less competition to weeds than the same species grown for hay. Furthermore, seed production schedules do not include frequent mowings, which might control some of the weeds. Practices favoring the competitive ability of the legume plant often cannot be utilized for controlling weeds in seed crops. Heavy vegetation growth may drastically reduce seed yield. Some tillage operations are occasionally used for weed control under such situations. Flaming of legume stubble in the early spring between hay cutting and seed crops may be utilized to destroy seedlings and attack dodder and other annual weeds. However, cultural practices alone seldom result in complete weed control in legume fields. Herbicidal control methods have been developed for these situations. Substituted urea (e.g., diuron) or triazine (e.g., simazine) herbicides have been developed for some of these situations. They are particularly effective for controlling the winter annual weeds that occur in the crops.

Many of the same principles of weed control used to establish legumes also apply to the establishment of grasses, although the herbicides utilized may be different. Annual broadleaf weeds offer severe competition to grasses. However, after the seeded grasses reach the two- to four-leaf stage of growth, they may be able to tolerate low rates of such herbicides as 2,4-D and dicamba. Weed grasses are quite difficult to control. In Oregon herbicides have been used effectively before and after grass planting. The seedbed is prepared in the fall, and the soil is treated with IPC and 2,4-D in January to control weeds and volunteer crop plants. Paraquat may be applied to later germinating weeds in March just before seeding the perennial grasses. By fall the perennial grasses may be so well established that the soil can be treated with diuron to control winter annual weeds.

An outstanding example of the importance of weed control and grass establishment was demonstrated in the southern United States. Coastal Bermuda grass planted in May was sprayed immediately afterward with simazine. Weeds were eliminated, and the grass yields amounted to 3.7 tons per acre of dry matter, as compared with 1.9 tons per acre of Bermuda grass and 1.6 tons per acre of weeds from an untreated plot. The treated area yielded 9.5 tons per acre the following year, but the untreated plot yielded only 6 tons per acre of Bermuda grass. The weed-control practice that was employed made possible better utilization of fertilizer by the forage grass, earlier grazing, and higher quality forage (Monson *et. al.*, 1971).

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INDUSTRIAL AND URBAN SITES

Utility Rights-of-Way

Electric Transmission Lines.—All woody vegetation that could ultimately reach the electric conductors on transmission lines must be controlled to prevent shorting of circuits and subsequent damage to equipment and loss of service. Many utilities have sought to eliminate all woody vegetation from transmission rights-of-way, but the current trend is to control only tall-growing trees and shrubs, allowing low-growing woody vegetation to remain. Transmission line rights-of-way are usually 100 to 500 feet wide.

An access road is also required for the maintenance and repair of the transmission structures and lines. Some of these roads are improved, but most have a cover of herbaceous vegetation. Grass is the preferred cover in most areas. No woody vegetation should be present on the access road.

Most utilities also remove any "danger timber" on, or adjacent to, the right-of-way that could reach and damage the transmission towers, poles, or conductors if it fell or was knocked down. In areas subject to fire, all vegetation is removed around wood poles and towers.

Electric Distribution Lines.—All woody vegetation must be controlled before it reaches the electrical conductors. Access roads are not usually maintained on the right-of-way, but it should be accessible by foot or vehicle. Brambles, briars, and poison ivy restrict access and should be removed. Distribution rights-of-way are usually 30 to 50 feet wide. In areas subject to fire, all vegetation is controlled around wooden poles.

Communication Lines.—Requirements for vegetation control are similar to those for electrical distribution lines. Communication cables are often carried on the same poles as electric conductors. Contact of the cables with vegetation is less critical, but cable wear due to friction with woody vegetation must be eliminated.

Gas and Fluid Transmission Lines.—Woody vegetation that would limit access must be controlled, but it is desirable to maintain a herbaceous or shrub cover to aid in detecting leaks in buried pipelines. Surface pipelines require total vegetation control for access, inspection, maintenance, and air circulation.

Mechanical Control

Hand Cutting.—Vegetation on most utility rights-of-way can be maintained by hand cutting. It can be cut totally or selectively, although labor costs are higher for selective cutting. Annual cutting is usually required. Disposal of the cut material by chipping is usually necessary, since burning is prohibited in many areas. Initial clearance of rights-of-way is by cutting and burning or chipping. Marketable wood products may be sold. The main limitation to hand cutting is its cost. The work is also difficult and hazardous.

Seeding or Planting.—Many rights-of-way can be seeded or planted with grass, hay, Christmas trees, or crops. In metropolitan areas it is often possible to maintain rights-of-way by regular mowing once grass is established. Maintenance costs are high, but good public relations are fostered. Where the soil and location are suitable for crops, they may be grown by a permit or easement system.

Bulldozing, Disking, or Chopping.—Brush control by bulldozing or disking is positive and nonselective. The right-of-way is usually converted to annual broadleaf vegetation such as ragweed, fireweed, and kochia. On hilly terrain erosion is a problem after bulldozing or disking, and the establishment of vegetative cover is difficult. Rugged terrain restricts or prohibits the use of a bulldozer. "Bush-hogging" with a heavy-duty mower can be used, but regular mowing is required and thorny vines often take over the site.

Burning.—Burning usually cannot be used on rights-of-way because of heat damage to towers, poles, and cables; the resulting smoke and air pollution; and potential damage to adjacent areas.

Chemical Control

Chemical vegetation control can be applied to utility rights-of-way using broadcast or selective techniques (see Table 1).

Broadcast Applications.—The stem-foliage spray is the "standard" method of controlling brush on utility rights-of-way. A mixture of herbicide concentrate and water is applied to all the leaves and stems of the brush to be controlled. As the spray season progresses and brush becomes harder to kill because of reduced herbicide absorption due to plant maturity, 10 to 15 percent fuel oil may be added to the mixture. The spray is usually applied by hand-held brush guns at a volume of 150 to 500 (average 300) gallons of spray solution per acre, depending on brush density. The spray applicator may walk and spray each clump of brush, or he may ride the spray vehicle and direct the spray at the brush stems and foliage. Stem-foliage sprays give best results when applied during periods of active brush growth—usually mid-May to mid-August in the United States. Most stem-foliage sprays are applied by truck-mounted sprayers with positive-displacement pumps at pressures of 200 to 400 psi. The average cost of chemicals for a stem-foliage spray is $30 plus $50 for labor, for a total cost of $80 per acre.

The most commonly used herbicides are the following:

1. 2,4-D and 2,4,5-T mixtures, ester or amines (4 lb/100 gal)
2. 2,4,5-T, ester or amines (4 lb/100 gal)
3. 2,4-D and dichlorprop mixtures, ester or amines (4 lb/100 gal)
4. 2,4-D, ester or amines (4 lb/100 gal)
5. 2,4-D and picloram mixtures, amines (2.5 lb/100 gal)
6. AMS (50 lb/100 gal)

A variation of the ground stem-foliage method is the use of a fixed broadcast nozzle mounted on a vehicle to apply a continuous herbicide spray pattern to the right-of-way. The average application rate is 3 gallons of herbicide concentrate (12 pounds of phenoxy acid) in 50 to 100 gallons of water. The amounts of herbicide per sprayed acre are similar for high-volume and fixed-nozzle spraying. Application costs are lower for the fixed nozzle, but this method is effective only on level terrain and brush of uniform height.

Dormant-cane broadcast sprays are used to control brush in areas where the risk of spray drift to herbicide-sensitive crops makes it hazardous to spray during the growing season. Since dormant-cane sprays are applied when most woody plants have no leaves, fuel oil is used as a spray diluent for bark penetration. The oil-herbicide mixture is sprayed on the stems and bases of the woody plants, usually by crewmen riding on a vehicle and holding a brush gun. Fixed nozzles are sometimes used. The standard herbicide mixture is 6 pounds of phenoxy herbicide in 98.5 gallons of fuel oil. Oil-soluble phenoxy-picloram combinations are sometimes used.

Dormant-cane broadcast sprays are very effective on such species as oak, ash, maple, and pine, which are resistant to foliage sprays. Dormant-cane sprays of phenoxy herbicides are not effective on root-suckering species, such as black locust, sassafras, sumac, and persimmon.

The average cost for dormant-cane treatments is $55 per acre for chemicals and $60 per acre for labor, for a total cost of $115 per acre.

Aerial broadcast spraying is usually done in the growing season when vegetation is in full leaf. It is most economical on rough, steep terrain or in swampy or inaccessible areas. Helicopters with conventional spray nozzles may be used. Since prevention of spray drift to adjacent areas is usually necessary, however, one of these industry-developed drift-control systems is generally used:

1. Bifluid invert system
2. Invert Spra-Disk System
3. R-511 + Norbak System
4. Microfoil boom

The volume of carrier used for aerial sprays varies from 5 to 30 gal/acre. Larger volumes are required for coverage as droplet size increases.

The average rate per acre is 3 gallons (12 pounds) for phenoxy herbicides and 2 to 4 gallons (5 to 10 pounds) of phenoxy-picloram mixtures. The average cost per acre is from $40 to $60. The advantages of broadcast spraying are as follows:

1. Useful for heavy mixed brush
2. Quick topkill of rapidly growing brush
3. Elimination of easy-to-kill species
4. Most efficient method for initial control of right-of-way brush

The disadvantages of broadcast spraying are as follows:

1. "Brownout" of brush foliage
2. Elimination of many desirable low-growing plants that provide game food and cover and soil protection
3. Drift potential of high-pressure or broadcast sprays
4. Heavy exposure of crews to herbicide sprays
5. Application of herbicide to nontarget areas

Table 1. HERBICIDES FOR INDUSTRIAL WEED AND BRUSH CONTROL

Chemical	Primary use	Primary mode of action	Rate (lb/acre)	Advantages	Disadvantages
Amitrole and amitrole-T	Grass control; perennial weed control; general weed control; knockdown of vegetation in combination with other herbicides	Foliage systemic	2-10	Broad spectrum, both grass and broadleaf weeds; no soil residue	Slow acting drift may cause chlorosis in susceptible plants
AMS	Brush control near sensitive crops and on watersheds	Foliage contact; root absorption	50-200	Drift does not harm sensitive crops	Corrosive; high rates required; skin irritation on prolonged contact
Atrazine	Residual weed control	Root absorption	2-40	Seasonal weed control	Poor on southern grasses; annual grasses reinvade soon
Bromacil	Perennial grass control; residual weed control; brush control	Root absorption	2-20	Controls johnsongrass	Leaches readily; injurious to desirable woody plants
Bromoxynil	Broadleaf weed control where phenoxy materials are hazardous or prohibited	Foliage contact	0.5-2	No drift hazard; for broadleaf control	Ineffective on grasses
Cacodylic acid	Knockdown of vegetation	Foliage contact	3-10	Rapid disappearance from soil	Caution needed in application
CBM (chlorate-borate mixtures)	Knockdown of vegetation; johnsongrass control	Foliage contact	50-800	Easy to spread as granules	High rates required
Dalapon	Postemergence grass control; controls johnsongrass and Bermuda grass	Foliage systemic	5-40	Controls most grasses	Retreatment usually required
Dicamba	Broadleaf weed control; brush control; usually used with phenoxies	Foliage systemic; root absorption	0.25-10	Kills several resistant brush species and broadleaf perennials; selective on grass	Drift injury to sensitive crops
2,4-D	Broadleaf weed control; brush control; used with other phenoxies	Foliage systemic	0.5-12	Low cost; broad spectrum; short soil residue; selective on grass	Drift injury to sensitive crops
Dichlorprop	Brush control with other phenoxies	Foliage systemic	2-8	Kills oaks as well as 2,4,5-T; selective on grass	Drift injury to sensitive crops
Dinoseb	Knockdown, oil fortifier	Foliage contact	1-12	Broad spectrum	Stains; toxic; no residual control
Diuron	Residual weed control	Root absorption	2-40	Long lasting; little injury to woody plants	Poor on organic soils
DSMA-MSMA	Grass knockdown; johnsongrass control used with phenoxies for brush control	Foliage contact	2-8	Low cost; kills annual grasses; repeat sprays kill rhizome johnsongrass	Caution required in application; needs high temperature for best results

Table 1. HERBICIDES FOR INDUSTRIAL WEED AND BRUSH CONTROL—Continued

Chemical	Primary use	Primary mode of action	Rate (lb/acre)	Advantages	Disadvantages
Fenac	Residual broadleaf weed control; annual grass control	Root absorption	3-18	Kills many perennial broadleaf weeds and annual grasses; kills resistant annuals; water soluble liquid	Slow acting; no perennial grass control
Herbicidal oils	Knockdown of vegetation	Foliage contact	10-100 gal	Fast acting	No residual action; no perennial weed control
Hexachloroacetone	Oil fortifier for control of railroad weeds and johnsongrass	Foliage contact	1-3 gal	Use as spot treatment; basal spray for johnsongrass; short soil persistence	
Karbutilate	Residual weed control; brush control	Root absorption	2-20	Controls many perennials and herbaceous brush species	No dandelion control; destroys ground cover as brushkiller
Linuron	Short-term residual control alone or in mixtures	Root absorption	1-4	Short-term soil residual; area may be reseeded or planted in 3-4 months	Many resistant species
Monuron	Residual weed control	Root absorption	2-40	Broad spectrum; controls many perennials	Leaches readily; injures desirable woody plants; no plantain control; poor on organic soils
Paraquat	Knockdown of grass and broadleaf weeds	Foliage contact	0.25-1	Broad spectrum; no soil activity	Hazardous to apply
Picloram	Brush control; broadleaf annual and perennial weed control; used with phenoxies	Foliage systemic; root absorption	0.25-8	Broad spectrum; grass very tolerant	Runoff injury; root uptake injury by desirable plants; ash and alder resistant
Pentachlorophenol	Knockdown of vegetation; oil fortifier	Foliage contact	10-20	Short persistence in soil	Toxic; causes skin, eye, and respiratory irritation; breaks down rubber
Prometone	Knockdown and residual control of annual and perennial broadleaf and grass weeds	Foliage systemic; root absorption	10-60	Controls southern grasses at high rates; broad spectrum; fast knockdown	Adequate rainfall required to kill perennials
Silvex	Brush control, broadleaf perennial control	Foliage systemic	1-8	Kills oaks, persimmon, and other brush	Not effective on all species; slow acting; more persistent in soil than other phenoxies
Simazine	Residual weed control	Root absorption	2-40	Little hazard to woody plants; leaches little	No control of southern grasses
Sodium arsenite	Knockdown; residual weed control	Foliage contact; root absorption	4-8	Broad spectrum	Toxic to domestic animals and wildlife; arsenic buildup; illegal in many areas
2,4,5-T	Brush control	Foliage systemic	1-8	Broad spectrum; versatile and selective on grass	Drift injury to sensitive plants

Table 1. HERBICIDES FOR INDUSTRIAL WEED AND BRUSH CONTROL–Continued

Chemical	Primary use	Primary mode of action	Rate (lb/acre)	Advantages	Disadvantages
TBA	Perennial broadleaf control; brush control	Root absorption	4-20	Effective on bindweed, knapweed, and other deep-rooted perennials; controls conifers	High rates, requires narrow spectrum
TCA	Perennial grass control	Foliage contact; root absorption	50-200	Short soil persistence	Corrosive; irritating to apply

Selective Applications.—Basal sprays are used to selectively control individual stems or clumps of brush. A herbicide-oil mixture is directed at a low pressure to the lower 12 to 18 inches of the brush stem in a sufficient quantity to puddle around the base or root collar. The standard basal spray concentration is 12 to 16 pounds of 2,4,5-T or a 2,4-D plus 2,4,5-T mixture per 100 gallons of fuel oil or kerosene. A mixture of picloram and 2,4,5-T or 2,4-D and dichlorprop is also used. The volume of spray per acre varies with the brush density but averages 100 to 150 gal/acre. Basal sprays are used not as initial applications to dense brush but as "cleanup" sprays to remove resistant species when easy-to-kill brush has been controlled. They can be applied at any season of the year, whenever the brush is not wet. Hand or power equipment may be used.

A recent variation of the basal spray is the use of the backpack mistblower to apply a more concentrated herbicide-oil mixture to brush. A mixture of 10 to 14 gallons of phenoxy herbicide concentrate per 100 gallons fuel oil or kerosene (equal to active ingredient by weight of 40 to 56 lb/100 gal) is used. Although the spray solution is more concentrated, herbicide rates per acre are about the same as in the case of conventional basal sprays since the volume per acre is from 25 to 40 gallons. A conventional basal spray application costs approximately $34 for chemicals and $45 for labor, for a total of $79 per acre. Mistblower basals cost $23 for chemicals and $35 for labor, for a total cost of $58 per acre.

Stump sprays are used for initial right-of-way clearance or to control brush sprouting after cutting. Oil-herbicide mixtures used for basal spraying are also used for stump spraying. The spray solution is applied to the stump and exposed roots. Truck-mounted power sprayers, backpack pump sprayers, or portable mistblowers are used to apply stump sprays. Average stump-spray costs are $23 for chemicals and $25 for labor, for a total cost of $48 per acre.

The advantages of basal and stump spraying are as follows:

1. Selectivity: only tall-growing woody plants need to be sprayed
2. Can be applied at any season
3. Minimum disturbance to ground-cover vegetation
4. Little or no "brownout"
5. Good control of "resistant" brush species
6. Little or no injury to off-right-of-way vegetation
7. Economical on scattered brush

8. Simple equipment can be used

9. Minimum environmental impact

The disadvantages of basal and stump spraying are as follows:

1. Poor control of root-suckering brush species
2. Too expensive on dense brush
3. Possible to miss some stems
4. Good supervision and instruction of spray crews needed

Soil/root treatments are usually applied as pellets or granules. Herbicides that are relatively persistent in the soil and are active on woody plants are used for soil applications. Treatments may be applied to individual brush clumps on a grid pattern (i.e., every 3 feet) or broadcast. Individual clump or grid treatments are usually applied by hand; broadcast applications are made by hand spreaders, truck- or trailer-mounted power spreaders, or helicopter-mounted spreaders. The herbicides commonly used for brush control are picloram, karbutilon, fenuron, TCA-monuron, and bromacil. The advantages of soil/root applications are as follows:

1. Can be applied selectively
2. Little or no equipment required
3. No drift problem

The disadvantages of soil/root applications are as follows:

1. High cost
2. Often injurious to ground-cover plants, which opens soil to erosion
3. Runoff injury adjacent to right-of-way
4. Easy to overdose
5. Soil persistence
6. Soil differences can affect results
7. Higher rates of herbicide required

Railroads

Yards and Switches.—It is necessary to maintain nearly 100 percent vegetation control for the safety of men working on foot in the area, for proper functioning of switches, for visibility, and for drainage. Vegetation control is difficult because the area is often high in carbon content from coal residue; grain spillage causes heavy sprouting of crop and weed seeds; and the area between adjacent tracks is subject to heavy leaching due to concentrated runoff from standing freight cars. The average annual vegetation-control costs are $50 to $150 per acre.

Ballast.—Total vegetation control is necessary in the ballast area to maintain drainage to keep the ballast free from fouling by soil or vegetation residue and to keep the ties dry to extend tie life. Ballast is usually coarse crushed rock. Annual weeds are not common, but perennial weeds often encroach from the berm area. The average annual vegetation-control costs are $10 to $30 per acre.

Shoulders and Berms.—The shoulder and berm area is immediately adjacent to the ballast. It is necessary to control large annuals, creeping perennials, and vines. Low-growing annuals can remain if they will not creep into the ballast area. Woody shrubs, perennials, and vines often grow in this area and extend into the ballast. The control of annuals has intensified the perennial and woody plant problem in this area. The average annual vegetation-control costs are $20 to $40 per acre.

Ditches and Adjacent Rights-of Way.—Railroad rights-of-way usually have drainage ditches in the track area. Herbaceous vegetation is desirable, but woody plants and vines must be controlled to maintain drainage and to prevent encroachment of vines into the berm and ballast area. States with strong weed-control laws often require the railroads to control noxious weeds in the right-of-way area even though they are not detrimental to the operation of the railroad (e.g., Canada thistle, knapweed, bindweed, and johnsongrass). The annual vegetation-control costs are $5 to $30 per acre.

Bridges and Structures.—Total vegetation control is required in the area adjacent to bridges and other structures, primarily for fire control. No vegetation residue is tolerated in this area. Most railroad structures are partially or totally constructed of wood. The average annual vegetation-control costs are $50 to $150 per acre.

Communication Lines.—Communication lines on wooden poles are often maintained on one edge of the railroad right-of-way. Lines are usually 10 to 15 feet above the ground. Brush must be controlled under these lines. Many railroads in arid areas control all vegetation under communication lines for fire control. Some require weed control only around the poles, but others need control all along the line since communication cables are damaged by heat. The average annual vegetation-control costs are $5 to $30 per acre.

Mechanical Control.—Vegetation in yards and switches can be controlled by hand cutting, but no acceptable equipment is available for mowing. Freightcars stand on the track much of the time, and engines and cars move about at all times. Hand grubbing and trimming around switches is possible, but would need to be done weekly in many areas. Wet vegetation is unsafe even if trimmed short in the walkways between tracks.

Ballast is periodically cleaned by machine. Vegetation in this area can be controlled by more frequent lifting and cleaning.

Vegetation on shoulders and berms can be mowed on a regular basis. Equipment exists for this use, and some railroads use it now. Vine control is difficult.

Mechanical weed control around bridges and structures is impractical since it would need to be done on such a regular basis. Vegetation residue would have to be removed.

On the balance of the right-of-way and under communication lines vegetation can be hand cut or mowed. The only limitations are cost and safety. Hand cutting brush is dangerous work, and poisonous snakes are problems in certain areas.

Chemical Control.*—Herbaceous weeds can be controlled by contact, translocated, or residual herbicides, but railroads commonly use a mixture of all three. The herbicide mixture and rate are determined by the weeds present, their location, and the degree of control needed. Where total control is needed, high rates of residual herbicides are used. For ballast and berm areas, contact or systemic herbicides combined with a low rate of residual material are commonly used. Granules are often used in yards, switches, and around bridges and structures, but high-volume sprays applied by spray train or highway-rail vehicles are used for ballast, shoulder, and berm weed control. A partial list of herbicides and rates used by railroads for herbaceous weed control is given in Table 1.

Chemical control of woody plants on railroad rights-of-way is primarily accomplished by high-volume (200 to 500 gal/acre) stem-foliage applications of phenoxy herbicides by spray trains mounted on the track. Application by highway-rail trucks is used on a small fraction of the acreage but is increasing. In areas adjacent to susceptible crops like cotton or tobacco, dormant-cane broadcast sprays or nonphenoxy, nonpicloram herbicides are used. The use of basal, cut-stump, and granular applications is negligible on railroad rights-of-way and is confined to inaccessible or heavily populated areas.

High-volume sprays are particularly suited for railroad application because of the ease with which tank cars of water or oil can be carried through the center of the area to be sprayed.

The control of herbaceous and woody vines, such as trumpetcreeper (*Campsis radicans*), peppervine species, redvine species, and various brambles (*Rubus* spp.), is more important for railroads than for other industrial consumers because these vines will grow over the ballast and track area, fouling the ballast, shortening tie life, and causing loss of traction.

Other Methods of Control.—Crops or hay can be grown on portions of some railroad rights-of-way, but the grazing of meat or dairy animals is not practical.

Industrial Areas

Situation and Nature of the Problem.—Vegetation must be controlled in industrial and commercial areas for access, inspection, fire prevention and control, air circulation, corrosion control, safety, and appearance. Industrial areas are quite diverse, and the level of vegetation control varies with the nature, location, and use of the area. Vegetation-control practices in industrial areas may be divided into classes based on the degree of control required: complete and partial or selective.

Situations requiring or commonly practicing complete control are (1) oil tank farms and refineries, (2) electrical substations, (3) storage areas and pole yards, and (4) industrial railroad sidings.

Situations requiring or commonly practicing partial or selective weed control are (1) parking lots, (2) drive-in movies, and (3) sign posts and outdoor advertising sightlines.

Mechanical Control.—Vegetation can be completely controlled in industrial areas by hand cutting or mowing; by bulldozing, blading, or scraping; and by controlled burning. In areas of seasonal rainfall mechanical vegetation control is mainly required during the rainy season, although some tall vegetation continues to grow during the dry or summer season. In areas of regular, nonseasonal rainfall, vegetation must be controlled for the entire growing season. Since access to the vegetation is often restricted by pipelines, structures, or stored materials, special implements are often required. Costs for mechanical control vary from $40 to $200 per acre, depending on the size of the area, nature of obstructions, climate, weather, and type of vegetation present. Burning can be used in some industrial areas but is impossible in refineries, petroleum-storage areas, and electrical substations. It is impractical in many storage areas.

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*See Table 1.

Chemical Control.*—Herbaceous weeds can be controlled by contact, translocated, or residual herbicides—or a mixture of all three. Herbicide mixtures are most commonly used. The herbicide mixture and rate are determined by the vegetation present and the degree of control needed. For total weed control high rates of residual herbicides are often used, particularly in oil tank farms and refineries. Where valuable woody vegetation is near the treated area, lower rates of residual herbicides are used. They are generally combined with systemic herbicides to provide "knockdown" of existing vegetation. Annual costs for chemical vegetation control range from $15 per acre in areas of seasonal growth to $200 per acre in areas of high rainfall and long growing seasons.

Woody plants growing in industrial areas are usually controlled by one or more of the techniques listed in the utility rights-of-way section. Where high rates of soil residual materials are used for total vegetation control, woody plants are usually not a problem.

Perennial weeds like johnsongrass, dogbane, milkweed, or Canada thistle in industrial areas may require spot treatment for satisfactory control. This technique requires less total herbicide on the treated area since the control of annual vegetation requires relatively low rates of a residual herbicide.

Potential Hazards.—Some potential hazards involved in weed control in industrial areas are the following:

1. Injury to vegetation in adjacent untreated areas by surface runoff or leaching of herbicides from rain or drainage water

2. Removal of cover and food plants for birds, rodents, and other wildlife

3. Increased erosion potential after vegetation removal

Ditch and Canal Banks

Ditches and canals are used for crop irrigation, stock watering, land drainage, transport, and recreation. It is necessary to control the vegetation on the banks of these ditches and canals in order to

1. Aid the flow of water for irrigation and drainage

2. Prevent or retard silt buildup in the ditch or canal by vegetation and refuse

3. Maintain access for maintenance and inspection

4. Prevent the spread of weed seed and plant parts by irrigation water and by wind and animals to adjacent land areas

5. Control burrowing animals to aid in restriction of water loss

6. Reduce water use by phreatophytes (water-using plants)

It is generally necessary to maintain some type of vegetation on the bank to prevent erosion of the bank. As a result, selective vegetation control methods are usually practiced.

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*Specific herbicides for industrial vegetation control are listed in Table 1.

Chemical Methods of Control.[*]—Since the water in the ditch or canal may be used for crop irrigation, stock watering, fishing, swimming, and human consumption, any herbicides that are applied to, or find their way into, the water must have established tolerances or be approved for use by the appropriate agencies. Techniques that permit the application of herbicides to the banks with a minimum of contamination of the water are important in ditch and canal bank spraying.

Woody Plants.—Woody plants on ditch and canal banks can be controlled by spray applications of 2,4-D, dichlorprop, silvex, picloram, dicamba, bromacil, or karbutilate—or by granular or pellet applications of picloram, bromacil, or karbutilate. 2,4,5-T may not be used on ditchbanks. Picloram may not be applied to the inner bank or bottom of irrigation ditches since contamination of water would result. Similar restrictions govern the use of the other herbicides. Ground applications use equipment or techniques that limit the herbicide to the bank, although some small amount of herbicide enters the water. Aerial applications on wide ditches are made to each ditchbank using drift-control equipment or techniques that limit the amount of herbicide entering the water. On narrow ditches both banks are often sprayed in one pass, with the aircraft centered over the ditch. More herbicide enters the water on these single-pass applications.

To control scattered brush, the conventional brush-control techniques listed under the utility rights-of-way section are often employed. Rates and volumes are similar to those reported in that section.

Herbaceous Vegetation.—Annual broadleaf weeds on ditch and canal banks can be controlled with a foliage spray of 2,4-D at rates of 1 to 4 lb/acre. Ground or aerial application equipment may be used, although ground equipment is most common where the bank is drivable. Application is usually made before seedheads are formed.

Perennial broadleaf weeds on ditch and canal banks generally require spot treatment with herbicides like 2,4-D, dicamba, fenac, TBA, or picloram. Eradication of perennial weeds on irrigation ditches is especially important to prevent the spread of noxious weed seeds or plant parts to cropland.

Perennial grasses may either present a hazard to cropland, as with johnsongrass, or may actually obstruct the flow of water, as with reed canarygrass, phragmites, or cattail. Spot or strip treatment with dalapon, amitrole-T, TCA, bromacil, or karbutilate is the general practice.

Mechanical Control.—Mowing or hand cutting of vegetation is possible on banks that are not steep and can be driven. Rocks, large trees or stumps, and uneven terrain limit the use of mowers. Trees and brush can be hand cut, subject to the limitations listed in the utility rights-of-way section. Ditches that have become overgrown and silted in can be restored to full flow by draglining or bulldozing.

DOMESTIC AND RECREATIONAL USES— WEED CONTROL IN TURF

Introduction

Turf is defined as "the upper stratum of soil bound by grass and plant roots into a thick mat." Grasses are the primary component of turf maintained intensively enough to require and justify weed control. Because of their basal, rather than apical, growth, grasses grow thickly and withstand constant clipping, providing a compact live cover that can be sustained indefinitely when handled properly. The primary turfgrasses in the northern cool-season area are Kentucky bluegrass (*Poa pratensis*), Colonial and creeping bentgrasses (*Agrostis* spp.), and certain fescues (*Festuca* spp.). In the southern warm-season belt Bermuda grass (*Cyhodon dactylon*), zoysia (*Zoisia japonica*), and St. Augustine (*Stenotaphrum secundatum*) are most important. About a dozen other species are significant locally, and scores of cultivars (cultivated varieties) have been selected for specific qualities.

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[*] See Table 1.

The physical characteristics and growth requirements of grasses differ considerably and determine their suitability as turf components for various conditions and purposes. In warm regions certain low-growing broadleaf plants are also used for turf. Chief among these are dichondra (*Dichondra repens*) and lippia (*Phyla nodiflora*).

The basic turf goal is to establish and maintain a uniform dense stand of predetermined species without unwanted grass or broadleaf species. Such a stand best performs the basic function of stabilizing soil and minimizing movement of soil particles. The binding network of roots and spreading runners controls erosion where water, wind, or wear would otherwise carry soil away. Good turf does this more efficiently than other plants that might occupy the same area, whether in the vast acreages of agricultural land and watersheds, along highways whose stability depends on a firm base, or on sloping lawns. Turfgrasses trap and hold dust and mud around homes, schools, and other public buildings and in playing fields, airfields, and similar installations, thus promoting health and comfort.

Turf absorbs and reflects solar energy. It may cool air several degrees by transpiration and evaporation, and in cool weather may prevent some heat loss from soil. It also reduces glare. The clipped turf of home lawns, athletic fields, and golf courses absorbs shock and reduces the risk of injury from falls. Turf is an excellent sound absorber, better than trees and shrubs because of its great surface area and resilience.

Good turf is an important decorative element in the landscape, providing an attractive setting for private or public buildings and natural or manmade ornaments. It adds spaciousness to outdoor living space and appreciable value to real estate. Along highways and around airports and industrial installations, turf provides safety as well as beauty, permits economical maintenance, and is an important element in soil conservation. Good turf is a basic part of multibillion-dollar sports activities such as golf with their many satellite investments of land, buildings, equipment, and manpower.

Historically, clipped turf is probably the outgrowth of grazing to prevent regrowth of cleared forests, and it continues to serve the same purpose in parks, historical sites, watershed areas, military lands, and other similar large-area situations. From that practice the fine turf now desired and necessary for many recreational purposes has gradually evolved.

Quality of turf may range from the open, informal populations of roadsides or meadows (mowed perhaps two to four times a year and often including low, broadleaf plants) to the ultimate of intensively groomed golf course putting greens with uniform fine grass daily mowed as close as 1/16 inch.

The greatest amount of turf is in home lawns, although other situations such as golf courses have more exacting requirements and standards, and hence demand more intensive management techniques. To establish a degree of perspective, comparative expenditures for annual maintenance alone are shown in Table 1. Since the figures were compiled, turf areas requiring intensive management (such as around condominiums, apartment houses, and industrial parks) have increased, and wages and other costs have risen fairly uniformly. Turfgrass is now considered to be a $12 billion industry.

Turfgrass culture reverses the usual concept of encouraging the ultimate size, flowering, and fruiting development of individual plants by removing competition. Instead, good turf requires crowding many grass plants into a given area, thus deliberately increasing competition by promoting vegetative growth. The degree of crowding depends largely on the type of turf to be developed. Turfgrass populations may range from 200 plants per square foot in a lightly grazed pasture to 20,000 in a fine putting green. The resultant plants are smaller and weaker than they would be if growing naturally. Thus a paradox of balancing the results of desirable competition with those of cultural skills is created.

Weeds (any unwanted plants) constitute the principal problem in establishing and maintaining good turf, far surpassing those of insects and diseases. Most weeds originate from seed or other reproductive organs in the soil of the turfed area or are introduced from surrounding areas. Weed-seed proliferation is enormous, and viability is usually notoriously long. A British study (Salisbury, 1961; p. 328) showed that 84 percent of ragweed and broadleaf plantain seed was still viable after 21 years of dormancy!

Turfgrass seed quality is regulated by federal and state laws. Purity, germination, percentage by weight of all crop and weed seed, and name and frequency of any noxious weeds present must be stated on the seed package.

Whether or not some plants, particularly certain grasses, are considered desirable or weedy may depend on the locality, manageability, and intended use. For instance, Bermuda grass is a basic turf component in the South, but may become an invasive nuisance farther north. Bentgrass, pampered to make fine putting greens, is a major weed in lawns. In areas subject to heavy traffic and in states with long, hot summers, tall fescue is eminently suitable, but it is obnoxious when mixed with finer textured grasses in northern lawns.

Weeds in turf impose the disadvantages already enumerated in preceding sections. For instance, crabgrass and dandelions compete for moisture, nutrients, and light. Plantains and garlic require additional maintenance time and labor. There are also weeds with poisonous, irritating, or other injurious characteristics, such as the spiny burs of sandspurs, and those that harbor insects and diseases (e.g., chickweed). Turfgrasses are already under the stress of competition even when the

Table 1. NATIONAL ANNUAL TURFGRASS MAINTENANCE EXPENDITURES BY SELECTED FACILITY[1]

Facility	Annual national expenditure	Percent of total
Airports	$34,606,352	0.8
Cemeteries	363,366,704	8.4
Churches	25,954,764	0.6
Colleges and universities	17,303,176	0.4
Golf courses	237,918,674	5.5
Highways	471,511,556	10.9
Lawns, residential	3,002,101,097	69.4
Lawns, commercial	25,954,764	0.6
Parks, municipal	60,561,117	1.4
Schools, public	38,932,147	0.9
Miscellaneous[2]	47,583,735	1.1
Total	4,325,974,086	100.0

[1] Source: Nutter (1965).

[2] Includes sod and seed production; municipal, state, and Federal government building lawns; state and Federal parks; private school facilities; professional athletic facilities; and others. Very conservatively estimated. For example, Florida alone grows approximately $10,000,000 worth of commercial sod yearly.

major factors of climate, soil, and management are favorable. This can be further aggravated by mechanical wear or other injury. Without proper care, aggressive weeds can quickly invade turf and reduce or nullify its functional and aesthetic purposes. When turf is thin because of unfavorable conditions, major weed invasion is inevitable, perpetuating a vicious cycle.

The competitive effects of weeds on crops have been determined numerically. For example, in an Illinois turf-establishment study (Madison, 1971; p. 75), when crabgrass was controlled in the planting, one-half to one-sixth as much grass seed was required to produce the same quality turf as where there was no crabgrass control.

Methods of Weed Control

Cultural Control.—Weeds in turf are generally the *result* of its poor quality, not the prime cause. Good quality is produced by proper preparation and management. This includes the appropriate choice of turf components; proper use of water, fertilizer, and pest controls; proper mowing practices; and avoidance of mechanical injury, including excessive wear. Proper application of principles varies from site to site, and especially from warm-season to cool-season turfgrass situations.

After weeds already established in the turf have been eliminated, further invasion can be controlled by providing proper nutrition, correcting inadequate or excessive drainage, aerating, and modifying extreme soil acidity or alkalinity, in addition to improving any weed-encouraging improper management practices, such as overwatering.

Where new turf is to be established, it is possible to induce some of the weed seed already in the soil to germinate before the turfgrasses are seeded, although this is inefficient and usually undesirable for other reasons. If perennial weeds (e.g., Canada thistle or quackgrass) are present, the area must be fallowed for one or more entire season.

Sodding instead of seeding minimizes the weed population, but it is expensive since producing good sod requires the practices already mentioned and some that follow.

Mechanical Control.—Mowing is the most common method of restraining weeds in turf, either through repressing plants like mustards and pigweeds, which are unable to tolerate constant close clipping, or by reducing seed production somewhat (a grass catcher should be used to remove mowed seedheads). However, mowing cannot eliminate the many species that are able to persist or produce seed at less than the cutting height. Many low-growing, mat-forming weeds (e.g., prostrate spurges, chickweeds, or crabgrasses) are in this category. Cutting height influences the quality of turf, the optimum varying with the grass species. Bluegrasses and fescues cut at less than 2 to 2.5 inches may die back, especially in hot dry weather, and allow weeds to invade. Conversely, bentgrass and Bermuda grass resist weeds best when cut 1 inch or lower. When allowed to grow higher, they tend to mat or to develop a loose, open growth that is subject to disease and subsequent weed invasion.

In increasing order of quality produced, equipment includes scythes, rotary mowers, flail mowers, sicklebar mowers, and reel mowers. Other related factors, such as mowing frequency and removing clippings and other debris, also influence turf health and hence the weed population.

Hand weeding might be advisable if there are relatively few weeds. Nonrhizomatous weeds like plantains or clump grasses can be eliminated by cutting below the crown. Hand weeding moderate or heavy infestations is impractical. Even if the amount of time required could be justified, seedlings and some other weed plants would inevitably be missed. It is just about impossible to remove creeping stem-rooting weeds like chickweed or maturing crabgrass manually or mechanically. Repeated defoliation may weaken some coarse grasses such as quackgrass.

Certain weeds resistant to other controls can be dug out and replaced by sod, especially if the infested area is not too large. Care must be taken to dig deeply and widely enough to remove all roots or stems capable of reproduction. Although grazing may be feasible for rough meadows or pastures where animals can be restricted and their droppings and soil compaction tolerated, it is unacceptable for any good turf.

Chemical Control.—Controlling weeds with chemicals has been attempted for centuries with little success until recently. The discovery of highly efficient and economical compounds during the last 30 years has afforded control that was formerly unattainable. Used properly, these materials accomplish tasks that are impossible with cultural and mechanical techniques. The increasing shortage and high cost of labor add to the importance of chemical weed control.

Herbicides may be selective, killing weeds but not the turfgrasses with which they are growing. These materials have a systemic effect, disorganizing metabolic processes of susceptible species. They may be absorbed by germinating seedlings—as in preemergence treatment for crabgrass control—or by expanded foliage—as in postemergence treatment of dandelions and many other weeds, especially broadleaved (dicotyledonous) ones. Contact herbicides, which kill any tissue they touch, are usually not selective. They are therefore useful where all vegetation is to be controlled, as in renovation work. Nonselective herbicides may be needed for weeds that do not respond to selective herbicides, such as muhlenbergia. Fumigants—volatile compounds applied to the soil—kill several types of living organisms, diseases, and insects as well as weeds.

Herbicides are used in different ways: before planting to ensure a weed-free seedbed, in newly seeded turf to minimize competition with emerging turfgrass seedlings, and in established turf to prevent the emergence of weeds or eliminate those already present. The chemicals used most commonly for these purposes are listed in Table 2 together with important considerations concerning their use.

The characteristics of a given compound may vary somewhat in different forms. For example, an emulsifiable ester formulation provides better penetration; a water-soluble amine is essentially nonvolatile. Liquid formulations are usually more efficient than granular forms of the same herbicide, requiring only about half as much active ingredient for the same effect. Liquid formulations affect plants more quickly and may also be dissipated sooner. They are harder than the more conspicuous granular formulations to apply accurately. Inaccurate equipment must be avoided in any case. Compounds are usually applied singly but may be combined to control a wider range of species in one operation.

Nearly all herbicides used for turf weed control have low mammalian toxicity and are readily decomposed in soil. They do not pose serious hazards to nontarget organisms when used as officially recommended. Rates of herbicide movement and decomposition in soil depend strongly on soil type, temperature, and moisture levels. The extent of leaching is retarded by organic matter and clay concent. Any volatility or photodecomposition will vary with temperature, light intensity, or method of application. Factors favoring soil microorganisms—organic matter, warmth, moisture—help accelerate the rate of microbial decomposition of herbicides in soil.

The satisfactory application of herbicides requires careful adherence to specific directions. Overdosing or underdosing will produce results different from those desired. Herbicides are intended to alter or prevent the growth of certain plants. Care must always be taken to avoid unintentionally injuring sensitive, desirable plants with drifting spray particles, careless practices, improper choice of chemical, or contaminating equipment used for nonherbicidal compounds. "Control is often simple; extermination may be expensive, ridiculous or impossible . . . a dense vigorous turf containing an occasional dandelion or crabgrass plant has weeds under control if weeds are few and fail to increase from season to season" (Madison, 1971, p. 155).

Table 2. CHEMICALS FOR TURF WEED CONTROL

Compound	Utilization	Rate (lb/acre)	Behavior	Disadvantages	Nonchemical alternatives
AMA	Homeowner and professional. Consistently excellent selective control of emerged crab, bahia, and dallis grasses; nutsedge; and sandspur. Most active of the methanearsonic herbicides. Can be used at early stage to eliminate need for higher rates later in season	2.5-3	Inhibits energy translocation; inactivated in soil by surface adsorption and ion exchange; effective 3-6 weeks	Severely injures St. Augustine, fescue, and centipede grasses; may require repeated application	Cultural (cut seedheads; mowing grass high; verticutting; fertilizing to shade out seedings next season)
Amitrole	Homeowner and professional. Short-term systemic for controlling emerged annual and perennial weed grasses as spot treatment or preliminary to lawn renovation. Superior translocation. Essentially nonselective. Treated areas can be reseeded soon after treatment.	2-6	Inhibits chlorophyll formation; broken down microbially in 2-3 weeks in moist, warm soil	Spray drift may produce albinism in desirable plants; phytotoxic effects slow to appear	Digging weeds out; smothering with impervious material; killing by cultural operations (fallow)
Atrazine	Professional. Controls winter annuals in warm-season grasses when applied before or early after emergence.	2-4	Inhibits photosynthesis; decomposed microbially; persists in soil 4-6 months. Downward leaching limited by adsorption to certain soil constituents.	May reduce stolon development; toxic to cool-season grasses	Hand weeding
Bandane	Homeowner and professional. Controls emerged crabgrass fairly well. Tolerated by dichondra and young turfgrasses.	30-35	Persists in soil 6-12 months or longer	Interferes with reseeding; has reduced Merion bluegrass rhizome production	Cultural (see AMA)
Benefin	Homeowner and professional. Controls emergence of crabgrass fairly well; also other weedy annual grasses and purslane.	1-2	Affects seed germination; strongly adsorbed on soil; negligible leaching. Decomposed by soil microorganisms. Effective 4-5 months.	Injures dichondra, bentgrass, and fineleaf fescues; may interfere with reseeding	Cultural (see AMA)
Bensulide	Homeowner and professional. Controls emergence of crabgrass fairly well and some annual broadleaf weeds. Promising for preventing annual bluegrass infestation. Tolerated by dichondra and established cool-season turfgrasses; safest preemergence herbicide for close-cut bentgrass.	10-20	Inhibits root development of germinating seed; persistent in soil	Persistent in soil; inhibits spring reseeding 3-6 months; affects newly sprigged Bermuda grass; may interfere with root development; should be watered into soil	Cultural (see AMA)

Table 2. CHEMICALS FOR TURF WEED CONTROL—Continued

Compound	Utilization	Rate (lb/acre)	Behavior	Disadvantages	Nonchemical alternatives
Bromoxynil	Homeowner and professional. Controls emerged seedling broadleaf weeds in seedling turf. By preventing weed competition, could eliminate further need for herbicides.	0.5	Inhibits photosynthesis and respiration; rapidly degraded by soil microorganisms	Not efficient on large, established weeds	Frequent mowing until grass is established is partial alternative
Cacodylic acid	Nonselective contact herbicide for killing emerged vegetation during lawn renovation. Permits reseeding in 2-5 days. Not absorbed by tree roots in treatment area.	5-20 lb/100 gal	Desiccant; quickly inactivated on contact with soil by surface adsorption and ion exchange	Mildly corrosive	Plowing or repeated cultivation
Calar	Homeowner and professional. Excellent selective control of emerged crabgrass, foxtail, nutsedge, dallisgrass. Less injurious to turfgrasses than AMA. Can be used 1-2 weeks after grasses emerge; tolerated by seedling bluegrass and fescues.	2-4	Kills germinating seed; effective 3-6 weeks	Injures St. Augustine grass; thins fineleaf fescues; may discolor turf temporarily; may require repeated application	Cultural (see AMA)
Calcium arsenate	Homeowner and professional. Prevents emergence of crabgrass; also controls chickweed and annual bluegrass in fall (in established turf).	500-1200	Interferes with energy translocation; persistent in soil	Has residual effects for 8-12 months. May thin perennial turfgrasses, especially with repeated use to maintain phytotoxicity. Toxicity to turfgrasses may increase in wet soils. Can be inactivated by high phosphorus in soil	Cultural (see AMA)
Chloropicrin	Professional. Excellent soil fumigant. Nonexplosive, nonflammable.		Kills most weed seed; controls soil microorganisms	Volatile; powerful irritant; lachrymator at low concentrations	Repeated cultivation; hand weeding
Dalapon	Homeowner and professional. Efficient grasskiller. Spot treatment for controlling annual and perennial grasses. Chemical "edger." Light rates (2-4 lb/acre) suppress grass growth. May be used on grasses in or near water.	4-8	Absorbed by roots and leaves; broken down rapidly and completely by soil microorganisms; leaches readily	Slow action (kills in 2-3 weeks); permits reseeding in 6 weeks. In sandy soils leachate may injure ornamental plantings.	Hand weeding; digging
Dazomet	Homeowner and professional. Soil fumigant. Also controls nematodes and soil-borne diseases. Does not require airtight seal; can be watered or tilled in.	5-6 lb/1000 ft^2	*Kills seedling weeds*	*Not as effective as methyl bromide.* Uncovered rhizomes may survive.	Repeated cultivation is partial alternative

Table 2. CHEMICALS FOR TURF WEED CONTROL–Continued

Compound	Utilization	Rate (lb/acre)	Behavior	Disadvantages	Nonchemical alternatives
DCPA	Homeowner and professional. Consistent preemergence crabgrass control under wide range of conditions. Also controls goosegrass and certain other annual grasses. Tolerated by bluegrass. Permits fall reseeding. Provides long residual control.	10-15	Kills germinating seeds; not translocated in plant. Adsorbed by organic matter in soil; limited leaching under normal rainfall conditions. Degraded microbially and by chemical hydrolysis. Average half-life is 100 days in most soil types.	May injure red fescue and bentgrasses. Highly organic soils require high rates. Persistent residue affects rhizome and tiller production; may interfere with reseeding.	Cultural (see AMA)
Dicamba	Homeowner and professional. Kills several broadleaf weed species missed by phenoxy herbicides (notably knotweed, spotted spurge, and sheep sorrel).	0.125-0.5	Plant-growth regulator; absorbed by roots and foliage; degraded microbially	Mobile in soil; injurious in root zone of a variety of herbaceous and woody plants if misused. Long residual life at rates higher than recommended for turf. Injures bentgrass, St. Augustine, and newly seeded lawns.	Hand weeding
2,4-D	Homeowner and professional. Most widely used broad-spectrum, selective, broadleaf weed killer. Also has some preemergence activity. Tolerated by seedling turfgrasses after first cutting. Treated areas can be reseeded in 2-4 weeks.	0.25-2	Plant-growth regulator; disturbs plant metabolism. Rapidly degraded in soil by microorganisms. Energy source for soil organisms.	Tolerated by chickweed, henbit, knotweed, spurge, sorrel, yarrow, and veronica. Drift may produce formative effects on sensitive desirable plants. May injure St. Augustine, centipede, bent, and newly emerged turfgrasses.	Hand weeding
DSMA	Homeowner and professional. Controls emerged crabgrass selectively in turf; also other weedy grasses and a few broadleaf weeds. Can remove paspalums from Bermuda grass and zoysias.	4-5	Inhibits energy translocation; inactivated in soil by absorption and ion exchange	Toxic to St. Augustine, centipede, and carpetgrasses; reduces bluegrass stands. May require repeated application. May discolor turfgrasses temporarily.	Cultural (see AMA)
Mecoprop	Homeowner and professional. Wide-spectrum, selective control of emerged broadleaf weeds. Safer than silvex on bentgrass and well tolerated by most other turfgrasses. Permits reseeding in 3-6 weeks; reduction slight after 1-2 weeks.	1.25-1.75	Plant growth regulator; decomposed by soil microorganisms	Slower acting phenoxy. Not as effective as 2,4-D; narrower weed-control spectrum. Drift may produce formative effects on sensitive ornamental or crop plants.	Hand weeding
Metham	Professional. Soil fumigant. Destroys all vegetation, weed seeds, nematodes, and	6-9 lb/1000 ft^3	Degraded by volatilization	Does not control uncovered rhizomes	Repeated cultivation is partial alternative

Table 2. CHEMICALS FOR TURF WEED CONTROL—Continued

Compound	Utilization	Rate (lb/acre)	Behavior	Disadvantages	Nonchemical alternatives
Metham (continued)	most soilborne organisms. Can be tilled or watered in 1 week before planting date.				
Methyl bromide	Professional. Soil-sterilizing fumigant. Kills weed seeds, vegetation, disease organisms, insects, and nematodes. Permits reseeding after 48 hours.	10-20 lb/1000 ft^3	Highly volatile except in gelled form; dissipated in 24-48 hours	Odorless. Requires airtight plastic seal and safety precautions during application. Inhalation of high concentrations may be fatal; nonfatal poisoning has occurred at 100-500 ppm. Extreme skin irritant. May kill beneficial soil organisms.	Repeated cultivation is partial alternative
Paraquat	Professional. General contact herbicide for quick, nonselective burning during turf renovation. Kills annual plants rapidly in bright sunlight. Does not accumulate in soil; permits seeding immediately. Eliminates need to disturb soil.	0.25-1	Desiccant; rapidly and completely inactivated by soil	Does not kill rhizomes. Irreversible inhalation effects may be lethal.	Repeated cultivation is partial alternative
Siduron	Homeowner and professional. Fairly good control of crabgrass emergence in turf. Also controls seedling spotted spurge. Tolerated by seedling and established cool-season turfgrasses. Removes Bermuda grass from bentgrass. Can be used on sod to be transplanted.	4-12	Root-growth inhibitor; not excessively persistent in soil; resists leaching; degraded by photochemical, chemical, and biochemical mechanisms	Prevents reseeding for about 2 months. Injures Bermuda grass and zoysia; may injure certain putting-green bentgrasses.	Cultural (see AMA)
Silvex	Homeowner and professional. Efficient selective broadleaf herbicide. Controls chickweed, yarrow, henbit, wood sorrel, clovers, pennywort, and spotted spurge not controlled by other phenoxy compounds. Translocates well.	3-4	Plant-growth regulator; disturbs normal processes of cell differentiation. Low water solubility. Adsorbed by soils with high organic matter content. Degraded more slowly than 2,4-D.	May persist in soil 4-8 weeks. Injures bent and St. Augustine grasses. Drift may produce formative effects on sensitive ornamental or crop plants. Smaller turfgrass safety margin than with 2,4-D or mecoprop.	Hand weeding is partial alternative
Simazine	Homeowner and professional. In warm-season turfgrasses only used for controlling broadleaf and grassy weeds before and early after emergence in sod production; not for use above North Carolina. Tolerated by St. Augustine, centipede, and zoysia grasses.	1-4	Inhibits photosynthesis. Degraded microbially. Downward leaching limited by low water solubility and soil adsorption. Little if any lateral movement; can move with soil particles. Absorbed by roots.	Persists 6-8 months; must be watered in	Hand weeding is partial alternative

Table 2. CHEMICALS FOR TURF WEED CONTROL–Continued

Compound	Utilization	Rate (lb/acre)	Behavior	Disadvantages	Nonchemical alternatives
Terbutol	Homeowner and professional. Affords fair selective preemergence crabgrass control. Tolerated by common turfgrasses.	10	Restricts root growth. Low water solubility, so slowly leachable. Persists 5 months in cool-season areas.	Injures bentgrass and fineleaf fescues on putting greens; must be watered into soil; prevents reseeding for 5-6 months	Cultural (see AMA)
Vorlex	Professional. Nonselective soil fumigant. Also active against insects, fungi, and nematodes.	0.5-1.5 gal/1000 ft^2		Must be injected and sealed in soil 4-5 weeks before planting date	Cultivation is partial alternative

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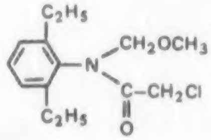
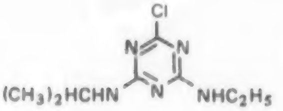
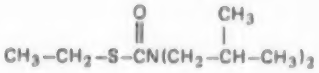
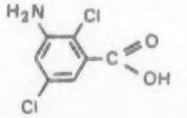
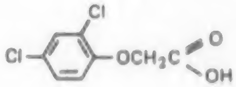
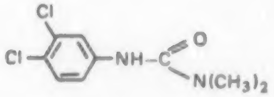
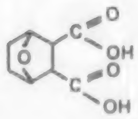
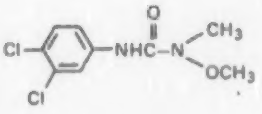
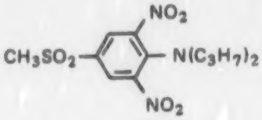
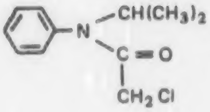
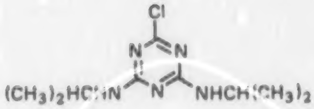
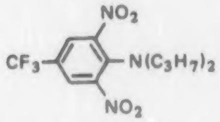
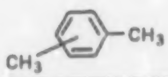
APPENDICES

Appendix I
STRUCTURE AND PHYSICAL PROPERTIES OF SOME HERBICIDES

Common name	Structure	Vapor pressure mm Hg (°C)	Solubility		
			Water	Acetone	Xylene (X) or benzene (B)
Acrolein	$CH_2=CH-CHO$	325 (30)	25%	Miscible	Miscible (X)
Alachlor		0.02 (100)	148 ppm	Soluble	Soluble (B)
Atrazine		3×10^{-7} (20) 1.4×10^{-6} (30)	33 ppm	1.8 g/100 g (methanol)	360 ppm (*n*-pentane)
Butylate	 $CH_3-CH_2-S-\overset{\overset{O}{\|}}{C}N(CH_2-\overset{\overset{CH_3}{\|}}{C}H-CH_3)_2$	13×10^{-3} (25)	45 ppm	Miscible	Miscible (X)
Chloramben		?	700 ppm	23 g/100 g	0.02 g/100 g (B)
Copper sulfate	$CuSO_4$	?	Soluble	?	?
2,4-D		6×10^{-7} (25)	600-700 ppm	45 g/100 cc	1.07 g/100 cc (B)
Diuron		0.31×10^{-5} (50)	42 ppm	5.3 g/100 g	0.12 g/100 g (B)
Endothall		?	10%	7 g/100 g	0.01 g/100 g (B)
Linuron		?	75 ppm	50 g/100 g	13 g/100 g (B)

STRUCTURE AND PHYSICAL PROPERTIES OF SOME HERBICIDES–Continued

Common name	Structure	Vapor pressure mm Hg (°C)	Solubility		
			Water	Acetone	Xylene (X) or benzene (B)
Nitralin	 NO2 CH3SO2 N(C3H7)2 NO2	$<1.5 \times 10^{-6}$ (25)	0.6 ppm	37 g/100 g	<12.5 g/100 g (B)
Propachlor	 N CH(CH3)2 C = O CH2 Cl	0.03 (110)	700 ppm	30.9%	50% (B)
Propazine	 Cl N N (CH3)2HC·HN N NHCH(CH3)2	2.9×10^{-8} (20)	8.6 ppm	Differs	diff. (X, B)
Trifluralin	 NO2 CF3 N(C3H7)2 NO2	1.99×10^{-4} (29.5)	< 1 ppm	1.19 (% molarity)	1.73 (X) (% molarity)
Xylene		Isomer:			
		o 6.62 (25)	196 ppm	Miscible	Miscible (B)
		m 8.30 (25)		Miscible	Miscible (B)
		p 8.76 (25)	198 ppm	Miscible	Miscible (B)

Source: Table prepared by E. E. Kenaga, July 1972.

Appendix II
GLOSSARY

Accumulation. See Bioconcentration.

Biennial. A plant that requires two growing seasons to go from seed to seed.

Bioaccumulation. Uptake and retention of environmental substances by an organism from its environment, as opposed to uptake of food.

Bioassay. A determination of the concentration or dose of a given material necessary to affect a test organism under stated conditions.

Bioconcentration. Action of a living organism in absorbing and retaining a foreign substance so that there is more in the organism than in the environment.

Biotransformation. Action of an organism in altering a foreign chemical compound.

Broadcast (blanket) application. An application of spray or dust over an entire area rather than only on rows, beds, or middles.

Carryover. Pesticide remaining from previous seasons.

Chromatography. Process of separating chemical compounds by allowing a solution to seep through an adsorbent (e.g., clay or paper) so that each compound becomes adsorbed in a separate layer.

Colorimetry. Technique of chemical analysis based on comparing a liquid's color with standard colors.

Cometabolism. Alteration of a chemical by an organism occurring only when a second compound is available as an energy source.

Condensate (or conjugate). Metabolite formed by joining pesticide molecule with molecule of another substance, e.g., glucuronic acid.

Degradation. Breakdown of a pesticide to other chemical species usually of simple structure.

Degradation product. Chemical species produced from applied pesticide, usually simple in structure.

Derivative chemical. Chemical formed from another for identification or for easier separation.

Directed spray. An application made to minimize the amount of herbicide applied to the crop. This is usually accomplished by setting nozzles low with spray patterns intersecting at the base of the plants just above the soil line.

Edema. Swelling.

Filamentous (algae). Threadlike.

Food chain. The transfer of food energy from plants or organic detritus through a series of organisms, usually four or five, consuming and being consumed.

Formulation. Physical and chemical form of pesticide prepared for specific use, e.g., emulsion granules.

Functional group. A characteristic reactive unit of a chemical compound.

Halogen. Any of the four elements fluorine, chlorine, bromine, and iodine.

Herbaceous plant. A vascular plant having little or no woody tissues .

Herbicide. A chemical used for killing or inhibiting the growth of plants.

Histology. A branch of anatomy that deals with the minute structure of animal and plant tissues as discernible with the microscope.

Hydrolysis. Chemical process of decomposition involving the splitting of a chemical bond and addition of the elements of water.

Incorporation in soil. Mixing of the herbicide with the soil, usually by mechanical means.

Isomeric. Chemical compounds having the same number of each atom but arranged differently.

Isotomic solutions. Solutions of equal osmotic strength.

LC_{50} (median lethal concentration) The concentration of a test material that causes death to 50 percent of a group of test organisms.

LD_{50} (median lethal dose). The dose of a test material, ingested or injected, that kills 50 percent of a group of test organisms.

Leach. Usually refers to percolating of water through a soil, which may move soluble components, such as chemicals or minerals.

Mass spectrometry. Technique for separating a stream of charged particles into groups according to the ratio of their charge to their mass.

Metabolism (of a pesticide). See Biotransformation.

Metabolite. New chemical species formed by biological action.

Microcoulometry. Technique of chemical analysis based on determining the amount of a substance released in an electrolysis.

Molluscicide. An agent, such as a chemical, for killing mollusks (e.g., pesticide).

Perennial. A plant that continues to live from year to year, renewing top growth seasonally or dying back seasonally and producing new growth.

Persistent pesticide. One that is destroyed only slowly by natural processes.

Photolytic (breakdown product). Of or relating to the formation of a chemical from another chemical by the action of light.

Photosensitizer. Chemical that causes light to have a harmful effect on a living organism.

Phytotoxic. Pertaining to or describing a substance poisonous to plants.

Phytotoxicant. Plant poison.

Phytotoxin. A poison derived from a plant.

Picogram. One-trillionth of a gram.

Plant pathogens. Agents, usually living, capable of producing diseases in plants.

Polarography. Method of analysis based on current-voltage curves obtained during the electrolysis of a solution with a steadily increasing electromotive force.

Postemergence. After emergence of a specified weed or crop.

Preemergence treatment. Treatment made after a crop is planted but before it emerges.

Preplanting treatment. Treatment made before the crop is planted.

Pyrolysis. Breakdown of molecules by heat.

P-value. Partition coefficient ratio of solubilities in two immiscible liquids.

Radiolabeling. Synthesis of compounds containing a radioactive isotope to permit tracing by radiation-detection equipment.

Reagent. Substance used in detecting or measuring a compound or preparing a compound because of its chemical activity.

Residues. That which remains after a part has been removed, taken, or separated.

Selective. Affecting some species much more than others.

Selective herbicide. A compound that is more toxic to the weeds than to the crop in the field.

Soil sterilant. Chemical capable of killing every living thing in the soil.

Spectrophotometry. Technique for measuring the relative intensities of the light at different wavelengths.

Spot treatment. Application of sprays to localized or restricted areas, as differentiated from broadcast coverage.

Spray drift. The movement of airborne spray particles from the spray nozzle beyond the intended contact area.

Synthesis. Making a chemical from simple chemicals.

Target species. Plant species to be destroyed.

Tolerant. Withstanding the action of a substance (e.g., pesticide) or condition without harm.

Translocation. Movement or transfer of a substance (e.g., chemical) from one location to another location within a plant.

Vapor drift. The movement of vapors from the area of application to other areas.

Weed. A plant growing where it is not desired.

Appendix III

COMMON AND CHEMICAL NAMES OF HERBICIDES[a]*

Common Name or Designation	Chemical Name[b]
acetochlor (à sē′ tō klōr)	2-chloro-*N*(ethoxymethyl)-6′-ethyl-*o*-acetotoluidide
acrolein (ȧ krō′le in)	acrolein
alachlor (ăl′ȧ chlôr)	2-chloro-2′,6′-diethyl-*N*-(methoxymethyl)acetanilide
ametryn (ăm′ē trin)	2-(ethylamino)-4-(isopropylamino)-6-(methylthio)-*s*-triazine
amiben (see chloramben)	
amitrole (ăm′i trōl)	3-amino-*s*-triazole
AMS	ammonium sulfamate
asulam (ăs′ ū lăm)	methyl sulfanilylcarbamate
atraton (ă′trȧ tōn)	2-(ethylamino)-4-(isopropylamino)-6-methoxy-*s*-triazine
atrazine (ă′trȧ zēn)	2-chloro-4-(ethylamino)-6-(isopropylamino)-*s*-triazine
barban (bär′băn)	4-chloro-2-butynyl *m*-chlorocarbanilate
benefin (bĕn′ĕ fĭn)	*N*-butyl-N-ethyl-α,α,α-trifluoro-2,6-dinitro-*p*-toluidine
bensulide (bĕn′sŭl id)	*O,O*-diisopropyl phosphorodithioate *S*-ester with *N*-(2-mercaptoethyl)benzenesulfonamide
bentazon (bĕn′tă zōn)	3-isopropyl-1*H*-2,1,3-benzothiadiazin-(4)3*H*-one 2,2-dioxide
benthiocarb (ben thi o carb)	*S*-[(4-chlorophenyl)methyl] diethylcarbamothioate
benzadox (bĕn′zuh dōx)	(benzamidooxy)acetic acid
benzipram (′ben zi pram)	*N*-benzyl-*N*-isopropyl-3,5-dimethylbenzamide
bifenox (bī′ fē năks)	methyl 5-(2,4-dichlorophenoxy)-2-nitrobenzoate
bromacil (brō′mȧ sil)	5-bromo-3-*sec*-butyl-6-methyluracil
bromoxynil (brō mŏx′ȳ nĭl)	3,5-dibromo-4-hydroxybenzonitrile
butachlor (byū̆t′ a klōr)	*N*-(butoxymethyl)-2-chloro-2′,6′-diethylacetanilide
butam (bjü′ taam)	2,2-dimethyl-*N*-(1-methylethyl)-*N*-(phenylmethyl)propanamide
butralin (bü′ trä lin)	4-(1,1-dimethylethyl) -(1-methylpropyl)-2,6-dinitrobenzenamine
buturon (bū′tū rōn)	3-(*p*-chlorophenyl)-1-methyl-1-(1-methyl-2-propynyl)urea
butylate (bū′tĭ lāt)	*S*-ethyl diisobutylthiocarbamate
cacodylic acid (că′cō dȳl′ic)	hydroxydimethylarsine oxide
carbetamide (cär bĕt′ ȧ mide)	*D*-*N*-ethyllactamide carbanilate (ester)
CDAA	*N,N*-diallyl-2-chloroacetamide
CDEC	2-chloroallyl diethyldithiocarbamate
chloramben (klōr ăm′bĕn)	3-amino-2,5-dichlorobenzoic acid
chlorazine (klō′ rȧ zēn)	2-chloro-4,6-bis(diethylamino)-*s*-triazine
chlorbromuron (klōr′ brōm u ron)	3-(4-bromo-3-chlorophenyl)-1-methoxy-1-methylurea
chloroxuron (klō rŏx′ū rōn)	3-[*p*-(*p*-chlorophenoxy)phenyl]-1,1-dimethylurea
chlorpropham (clôr prō′făm)	isopropyl *m*-chlorocarbanilate
CIPC (see chlorpropham	
CMA	calcium methanearsonate
cyanazine (cī-ăn′-ȧ-zēn)	2-[[4-chloro-6-(ethylamino)-*s*-triazin-2-yl]amino]-2-methylpropionitrile
cycloate (sy′clō āt)	*S*-ethyl N-ethylthiocyclohexanecarbamate
cycluron (sy′klū rōn)	3-cyclooctyl-1,1-dimethylurea
cyperquat (′si pər kwät)	1-methyl-4-phenylpyridinium
cyprazine (sī′prā zēēn)	2-chloro-4-(cyclopropylamino)-6-(isopropylamino)-*s*-triazine
cyprazole (sī′ prȧ zol)	*N*-[5-(2-chloro-1,1 dimethylethyl)-1,3,4-thiadiazol-2-yl]cyclopropanecarboxamide
cypromid (sy′prō mĭd)	3′,4′-dichlorocyclopropanecarboxanilide
dalapon (dăl′ȧ pōn)	2,2-dichloropropionic acid
dazomet (dă′zō mĕt)	tetrahydro-3,5-dimethyl-2*H*-1,3,5-thiadiazine-2-thione
DCPA	dimethyl tetrachloroterephthalate
DCU	1,3-bis(2,2,2-trichloro-1-hydroxyethyl)urea
delachlor (dĕl ă klōr′)	2-chloro-*N*-(isobutoxymethyl)-2′,6′-acetoxylidide
desmedipham (dĕz′ mĕd ē făm)	ethyl *m*-hydroxycarbanilate carbanilate (ester)
desmetryn (dĕs′mē trin)	2-(isopropylamino)-4-(methylamino)-6-(methylthio)-*s*-triazine
diallate (dī′ăl lāt)	*S*-(2,3-dichloroallyl)diisopropylthiocarbamate
dicamba (dī kăm′bȧ)	3,6-dichloro-*o*-anisic acid
dichlobenil (dī′clō bĕn′il)	2,6-dichlorobenzonitrile
dichlormate (dī chlōr māte)	3,4-dichlorobenzyl methylcarbamate
dichlorprop (dī′clôr prŏp)	2-(2,4-dichlorophenoxy)propionic acid
dicryl (dī′ crĭl)	3′,4′-dichloro-2-methylacrylanilide
difenzoquat (dī ′fen zō kwät)	1,2-dimethyl-3,5-diphenyl-1*H*-pyrazolium
dinitramine (dī-nī′-trȧ-mēn)	N^4,N^4-diethyl-α,α,α-trifluoro-3,5-dinitrotoluene-2,4-diamine
dinosam (dī′nō săm)	2-(1-methylbutyl)-4,6-dinitrophenol
dinoseb (dī′nō sĕb)	2-*sec*-butyl-4,6-dinitrophenol
diphenamid (dī fĕn′ ȧ mĭd)	*N,N*-dimethyl-2,2-diphenylacetamide
dipropetryn (dī′ prop′ ē trȳn)	2-(ethylthio)-4,6-bis(isopropylamino)-*s*-triazine
diquat (dī′kwät)	6,7-dihydrodipyrido[1,2-α:2′,1′-*c*]pyrazinediium ion
diuron (dī′ū rōn)	3-(3,4-dichlorophenyl)-1,1-dimethylurea
DMTT (see dazomet)	
DNAP (see dinosam)	
DNBP (see dinoseb)	
DNC (see DNOC)	

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DNOC	4,6-dinitro-*o*-cresol
DSMA	disodium methanearsonate
endothall (ĕn′dö thâl)	7-oxabicyclo[2.2.1]heptane-2,3-dicarboxylic acid
EPTC	*S*-ethyl dipropylthiocarbamate
erbon (ûr′bŏn)	2-(2,4,5-trichlorophenoxy)ethyl 2,2-dichloropropionate
ethiolate (e thī′ ō lāte)	*S*-ethyl diethylthiocarbamate
EXD	*O*,*O*-diethyl dithiobis[thioformate]
fenac (fĕn′ăc)	(2,3,6-trichlorophenyl)acetic acid
fenuron (fĕn′ū rŏn)	1,1-dimethyl-3-phenylurea
fenuronTCA	1,1-dimethyl-3-phenylurea mono(trichloroacetate)
fluchloralin (flū klôr′ a lĭn)	*N*-(2-chloroethyl)-2,6-dinitro-*N*-propyl-4-(trifluoromethyl)aniline
fluometuron (flū ō mĕt′ū rŏn)	1,1-dimethyl-3-(α,α,α-trifluoro-*m*-tolyl)urea
fluorodifen (flūr ō dī′fĕn)	*p*-nitrophenyl α,α,α-trifluoro-2-nitro-*p*-tolyl ether
glyphosate (glī′fō sāt)	*N*-(phosphonomethyl)glycine
HCA	1,1,1,3,3,3-hexachloro-2-propanone
hexaflurate (hĕx′ á flōor′āte)	potassium hexafluoroarsenate
ioxynil (ī ŏx′ÿ nil)	4-hydroxy-3,5-diiodobenzonitrile
ipazine (ĭp′ á zēn)	2-chloro-4-(diethylamino)-6-(isopropylamino)-*s*-triazine
IPC (see propham)	
isocil (ī′sō sil)	5-bromo-3-isopropyl-6-methyluracil
isopropalin (ī′sōprō′pa lĭn)	2,6-dinitro-*N*,*N*-dipropylcumidine
karbutilate (kar byūt′l āt)	*tert*-butylcarbamic acid ester with 3-(*m*-hydroxyphenyl)-1,1-dimethylurea
KOCN	potassium cyanate
lenacil (lĕn′ á cil)	3-cyclohexyl-6,7-dihydro-1*H*-cyclopentapyrimidine-2,4(3*H*,5*H*)-dione
linuron (lin′ū rŏn)	3-(3,4-dichlorophenyl)-1-methoxy-1-methylurea
MAA	methanearsonic acid
MAMA	monoammonium methanearsonate
MCPA	[(4-chloro-*o*-tolyl)oxy]acetic acid
MCPB	4-[(4-chloro-*o*-tolyl)oxy]butyric acid
MCPES	2-[(4-chloro-*o*-tolyl)oxy]ethyl sodium sulfate
MCPP (see mecoprop)	
mecoprop (mĕc′ō prŏp)	2-[(4-chloro-*o*-tolyl)oxy]propionic acid
metham (mĕth′ăm)	sodium methyldithiocarbamate
methazole (mĕth′-á-zōl)	2-(3,4-dichlorophenyl)-4-methyl-1,2,4-oxadiazolidine-3,5-dione
metobromuron (mĕt′ō brom′ū rŏn)	3-(*p*-bromophenyl)-1-methoxy-1-methylurea
metribuzin (mĕ-trĭ-bu′-zin)	4-amino-6-*tert*-butyl-3-(methylthio)-*as*-triazine-5(4*H*)one
MH	1,2-dihydro-3,6-pyridazinedione
molinate (mō′lĭ nāt)	*S*-ethyl hexahydro-1*H*-azepine-1-carbothioate
monolinuron (mŏn′ō lin′ū rŏn)	3-(*p*-chlorophenyl)-1-methoxy-1-methylurea
monuron (mŏn′ū rŏn)	3-(*p*-chlorophenyl)-1,1-dimethylurea
monuronTCA	3-(*p*-chlorophenyl)-1,1-dimethylurea mono(trichloroacetate)
MSMA	monosodium methanearsonate
napropamide (nă prŏp′ a mide)	
naptalam (năp′tá lăm)	2-(α-naphthoxy)-*N*,*N*-diethylpropionamide
neburon (nĕb′ū rŏn)	*N*-1-naphthylphthalamic acid
nitralin (nī′trá lin)	1-butyl-3-(3,4-dichlorophenyl)-1-methylurea
nitrofen (nī′trō fĕn)	4-(methylsulfonyl)-2,6-dinitro-*N*,*N*-dipropylaniline
norea (nō rē′uh)	2,4-dichlorophenyl-*p*-nitrophenyl ether
norflurazon (nôr′ flūr a zăn)	3-(hexahydro-4,7-methanoindan-5-yl)-1,1-dimethylurea
NPA (see naptalam)	4-chloro-5-(methylamino)-2-(α,α,α-trifluoro-*m*-tolyl)-3(2*H*)-pyridazinone
oryzalin (ō rī′ ză lin)	3,5-dinitro-N^4,N^4-dipropylsulfanilamide
oxadiazon (ox′ a dī′ a zon)	2-*tert*-butyl-4-(2,4-dichloro-5-isopropoxyphenyl)-Δ^2-1,3,4-oxadiazolin-5-one
paraquat (pâr′ é kwät)	1,1′-dimethyl-4,4′-bipyridinium ion
PBA	chlorinated benzoic acid
PCP	pentachlorophenol
pebulate (pĕb′ū lāt)	*S*-propyl butylethylthiocarbamate
perfluidone (per′ flū ĭ dŏn)	1,1,1-trifluoro-*N*-[2-methyl-4-(phenysulfonyl)phenyl] methanesulfonamide
phenmedipham (fĕn mĕd′i făm)	methyl *m*-hydroxycarbanilate *m*-methylcarbanilate
picloram (pĭc′lôr ăm)	4-amino-3,5,6-trichloropicolinic acid
PMA	(acetato) phenylmercury
procyazine (prō ′sī a zēn)	2-[[4-chloro-6-(cyclopropylamino)-1,3,5-triazine-2-yl]amino]-2-methylpropanenitrile
profluralin (prō flūr′ á lĭn)	*N*-(cyclopropylmethyl)-α,α,α-trifluoro-2,6-dinitro-*N*-propyl-*p*-toluidine
prometon (prō′mĕ tōn)	2,4-bis(isopropylamino)-6-methoxy-*s*-triazine
prometryn (prō′mĕ trin)	2,4-bis(isopropylamino)-6-(methylthio)-*s*-triazine
pronamide (prŏn′ ä mide)	3,5-dichloro-*N*-(1,1-dimethyl-2-propynyl)benzamide
propachlor (prō′pá clôr)	2-chloro-*N*-isopropylacetanilide
propanil (prō′pá nil)	3′,4′-dichloropropionanilide
propazine (prō′pá zēn)	2-chloro-4,6-bis(isopropylamino)-*s*-triazine
propham (prō′ făm)	isopropyl carbanilate
prynachlor (prin′ ä klōr)	2-chloro-*N*-(1-methyl-2-propynyl)acetanilide
pyrazon (pī′rá zŏn)	5-amino-4-chloro-2-phenyl-3(2*H*)-pyridazinone
pyriclor (pī′rĭ clôr)	2,3,5-trichloro-4-pyridinol
sesone (sĕs′ōn)	2-(2,4-dichlorophenoxy)ethyl sodium sulfate
siduron (sĭd′ū rŏn)	1-(2-methylcyclohexyl)-3-phenylurea
silvex (sĭl′vĕks)	2-(2,4,5-trichlorophenoxy)propionic acid
simazine (sĭm′á zēn)	2-chloro-4,6-bis(ethylamino)-*s*-triazine
simeton (sim′ē tōn)	2,4-bis(ethylamino)-6-methoxy-*s*-triazine
simetryn (sĭm′ē trin)	2,4-bis(ethylamino)-6-(methylthio)-*s*-triazine
SMDC (see metham)	
solan (sō′lăn)	3′-chloro-2-methyl-*p*-valerotoluidide
swep (swĕp)	methyl 3,4-dichlorocarbanilate

tebuthiuron (tĕb ū thī´ ū rŏn)	*N*-[5-(1,1-dimethylethyl)-1,3,4-thiadiazol-2-yl]-*N*,*N*′-dimethylurea
terbacil (tĕr´bá cĭl)	3-*tert*-butyl-5-chloro-6-methyluracil
terbuthylazine (ter byü thĭl ă zēn)	2-(*tert*-butylamino)-4-chloro-6-(ethylamino)-*s*-triazine
terbutol (tĕr´bū tōl)	2,6-di-*tert*-butyl-*p*-tolyl methylcarbamate
terbutryn (tĕr´bū trĭn)	2-(*tert*-butylamino)-4-(ethylamino)-6-(methylthio)-*s*-triazine
TCA	trichloroacetic acid
triallate (trī´ ăl lāt)	*S*-(2,3,3-trichloroallyl)diisopropylthiocarbamate
tricamba (trī căm´bá)	3,5,6-trichloro-*o*-anisic acid
Triclopyr (´trī klō pir)	[(3,5,6-trichloro-2-pyridinly)oxy]acetic acid
trietazine (trī ĕt´ á zēn)	2-chloro-4-(diethylamino)-6-(ethylamino)-*s*-triazine
trifluralin (trī flŭr´ á lĭn)	α,α,α-trifluoro-2,6-dinitro-*N*,*N*-dipropyl-*p*-toluidine
trimeturon (trī mĕt´ ū rŏn)	1-(*p*-chlorophenyl)-2,3,3-trimethylpseudourea
2,3,6-TBA[c]	2,3,6-trichlorobenzoic acid
2,4-D	(2,4-dichlorophenoxy)acetic acid
2,4-DB	4-(2,4-dichlorophenoxy)butyric acid
2,4-DEB	2-(2,4-dichlorophenoxy)ethyl benzoate
2,4-DEP	tris[2-(2,4-dichlorophenoxy)ethyl] phosphite
2,4-DP (see dichlorprop)	
2,4,5-T	(2,4,5-trichlorophenoxy)acetic acid
2,4,5-TES	sodium 2-(2,4,5-trichlorophenoxy)ethyl sulfate
vernolate (vĕr´nō lāt)	*S*-propyl dipropylthiocarbamate

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[a] Herbicides no longer in use in USA are omitted. Complete listing, including these, is in WEEDS 14(4), 1966.

[b] As tabulated in this paper, a chemical name occupying two lines separated by an equal (=) sign is joined together without any separation if written on one line.

[c] This herbicide usually is available as mixed isomers. When possible, the isomers should be identified, the amount of each isomer in the mixture specified and the source of the experimental chemicals given.

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